Holzbau: Timber Construction and Material Information Exchanges for the Design of Complex Geometrical Structures

by

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ABSTRACT

In a universe made of bits where everything is continuously computing and nature itself is processing information everyday, what is it that our materials compute? Specifically, what are the bits of information registered within timber? More importantly, in this universe made of bits how do we design using this information and how do we imagine new buildings? This thesis explores the use of wood as a natural material in the design and construction of complex geometrical timber structures by capturing the natural curvature found in timber into digital data and building a framework for surface timber mapping as a design method. Key results include a detailed framework for translation, method for timber mapping and a prototype utilizing this method. Future steps include growth of timber structures and the use of living material in combination with typical timber construction methods for the design and construction of future buildings.

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Lastly, my wife Vanessa Aparicio, who has gone through this journey with me and has served as a point of inspiration along the way.

Thank You,

German Walter Aparicio Jr.

Table of Contents

1 Introduction

"The universe is the biggest thing there is and the bit is the smallest possible chunk of information. The universe is made of bits. Every molecule, atom, and elementary particle register bits of information. Every interaction between those elements processes information", (Lloyd, 2007).

In the book "Programming the Universe", Seth Lloyd Quantum Mechanic and Professor of Mechanical Engineering at the Massachusetts Institute of Technology describes the universe as molecules, atoms, and elementary particles which register bits of information and the interactions between these elements process information, essentially the universe is a computer and everything within it is continuously computing (Lloyd, 2007). This thesis is interested in what it is that our materials compute. Specifically, what are the bits of information registered within timber? What interactions and processes of information occur within this material? What computations occur during growth and construction? More importantly, in this universe made of bits how do we use this information for design? This thesis explores the use of wood as a natural material in the design and construction of complex geometrical timber structures.

Referenced in this thesis are two case studies, which included laminated timber roof structures of complex geometries. The focus of these case studies is in the use of wood as a building material and timber construction systems implemented in the design and construction of each building. Each of these case studies uses different timber construction systems and celebrates the use of wood in different ways. The purpose of this investigation is to find methods in which material curvature found in timber could be used in the design and construction of complex geometrical structures.

The approach taken in this thesis begins with 3d digitizing branch members into a 3d modeling environment and building a library of parts, which can be mapped onto any given surface. The intent is to approximate a surface through timber mapping and generating new forms using the natural curvature of each scanned member. The criterion for success is dependent on approximation of the surface and ability to use the library of parts.

2 Wood, Timber Construction and Natural Architecture

2.1 Wood

In a paper published by the US department of Transportation Federal Highway Administration the authors write about a material model developed to predict the dynamic performance of wood. This paper describes the behavior of wood as a variable material. Stiffness and strength properties vary as a function of orientation between longitudinal, tangential, and radial directions (Figure 1). The longitudinal direction is the fiber or grain direction, stiffness and strength are greatest in the fiber direction. The tangential and radial directions are transverse to the fiber direction, and tangential and perpendicular to the growth rings. Loading wood at angles to the grain has significant effects on strength. The failure modes and measured stress-strain relationships of wood depend on the direction of the load relative to the grain and the type of load(US Department of Transportation Federal Highway Administration, 2007).

Another factor that affects the measured stress-strain relationships is moisture content and temperature. Wood exhibits progressive softening, modulus reduction and permanent plastic deformation. Typically, the moduli strength of wood decreases as temperature increases. In addition, temperature interacts with moisture to influence the mechanical properties. Chemical changes in the wood properties produce large reductions in strength. Repeated exposure to elevated temperatures has a cumulative effect.

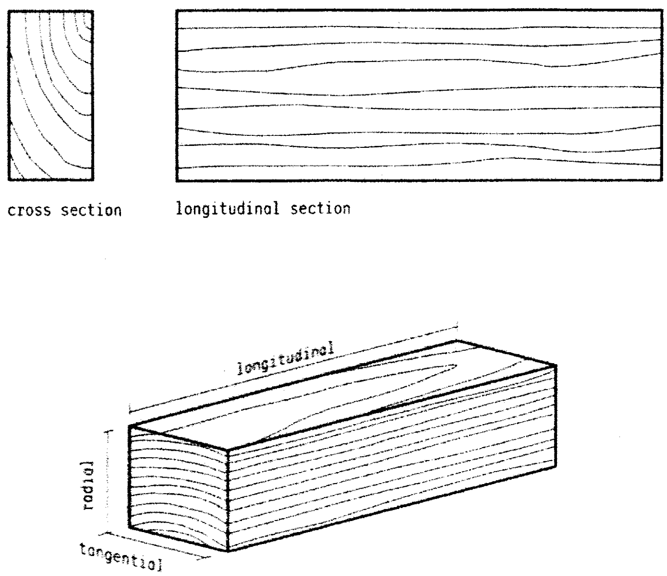


Figure 1 Timber Cut (Basics Timber Construction)

Growth

In this universe made of bits where everything within it is continuously computing, what is it that timber computes? How is it that trees grow? In a book titled "Design in Nature: Learning from Trees", Claus Mattheck describes tree growth regulators and their effects on tree shape (Figure 2) (Mattheck, 2004). Essentially, there are three growth regulators found in the growth and development of a tree. The first growth regulator is known as apical dominance. Apical dominance instructs branches to grow away from the tree trunk. This process allows branches to receive more light than would a bundle of branches. The second growth regulator known as Geotropism instructs the branches to grow erect against gravity. The third and last growth regulator known as Phototropism instructs the branches to grow towards light. Phototropism dominates the previous growth regulator, without light the tree will die (Figure 3) (Mattheck, 2004).

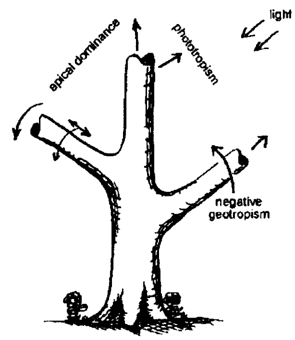


Figure 2 Tree Growth Regulators And Their Effect On Tree Shape (Design in Nature)

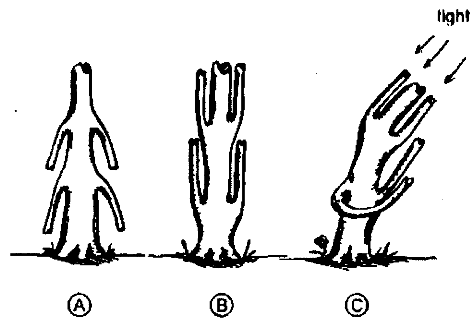


Figure 3 Success of Growth Regulators A: apical dominance B: geotropism C: phototropism (Design in Nature)

Cells

In addition to directional strength, the strength found in timber comes from its cellular structure. The structure of wood is composed primarily of long and slender cells called fibers. These cells have a hollow, tubular form with an orientation of their lengths in the longitudinal direction of the log. The fibrous, tubular cells of the wood are composed primarily of cellulose and the material that binds the cells are called lignin. These two materials are the main chemical components of wood giving wood, its cellular structural strength (Ambrose & Tripeny, 2009).

Early Wood / Late Wood

Transverse to the fiber is the radial direction. Loading wood at angles to the grain has significant effect on strength. The failure modes and measured stress-strain relationships of wood depend on the direction of the load relative to the grain and the type of load. Trees used for lumber in the United States are exogenous, they increase in size by growth of new wood on the outer surface under the bark. The cross section of a tree truck reveals the layers of new wood that are formed annually. These layers, called annual rings, are typically composed of alternating light and dark material. In most areas, the lighter, more porous layers are grown in the warmer months of the year, and the denser, darker layers are grown in the colder months. The number of layers of annual rings at the base of the tree trunk indicates the age of a tree. The youngest band of annual rings at the outer edge of the tree is called the sapwood. This is usually lighter in color than wood at the center of the log, which is called the heartwood (Figure 4).

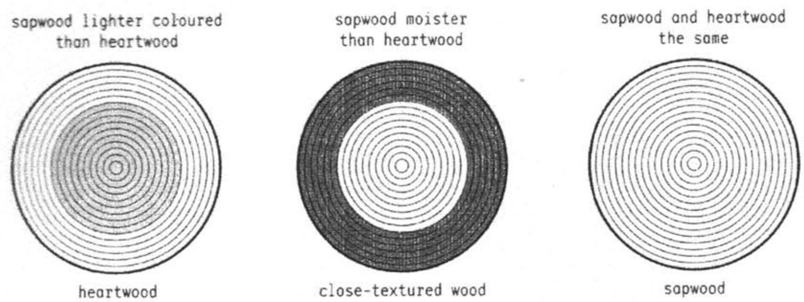


Figure 4 Heartwood and Sapwood Tree Cross Section (Basics Timber Construction)

Properties

During the growth and development of a tree certain properties such as density of wood and defects found from the natural growth process determine weather or not a given tree can be used for the construction of a building. There are no machine grading systems for round timber stems or cut timber of larger cross-sections. Visual evaluation is the method used in determining the quality of a tree stem.

Traditionally, the quality of timber used for load-bearing structures is assessed visually. The criteria include knot ratio (the size and frequency of knots in relation to the cross-sectional dimensions), the width of the annual rings, deviations in fiber orientation (deviation of the direction of wood fibers from the longitudinal axis of the cross-section), and damage to the stem caused by cracking, insects and fungi. The classification will also depend on the subjective judgment of the person grading the timber (Herzog, 2000).

Density of Wood

The strength of wood is closely related to its density. The difference in the arrangement and size of the cell cavities and the thickness of the cell walls determine the specific gravity, or relative density, of various species of wood. The solid material in wood is about 1.53 times the weight of water, but the wood cells contain open spaces in varying degrees.

Defects in Lumber

Any irregularity in wood that affects its strength or durability is called a defect. Because of the natural characteristics of the material, several common defects are inherent in wood.

A knot is a portion of a branch that has been surrounded by subsequent growth of the tree. The strength of a structural member is affected by the size and location of knots it may contain. Grading rules for structural lumber concern the number, size, and position of knots.

A shake is a separation along the grain, principally between annual rings. Shakes reduce the resistant to shear.

A check is a separation along the grain, the greater part of which occurs across the annual rings. Checks generally develop during the process of seasoning. Like shakes, checks also reduce the resistance to shear.

A split is a lengthwise separation of the wood that extends through the piece from one surface to another. Splits have a major effect in reducing shear resistance.

A pitch pocket is an opening parallel to the annual rings that contains pitch, either solid or liquid.

Types of Cut

The timber industry has standardized cuts and tries to optimize the types of cuts one can use in the design and construction of timber structures. The types of cuts available from a typical tree trunk include a lath, plank, board or squared timber (Figure 5, Figure 6).

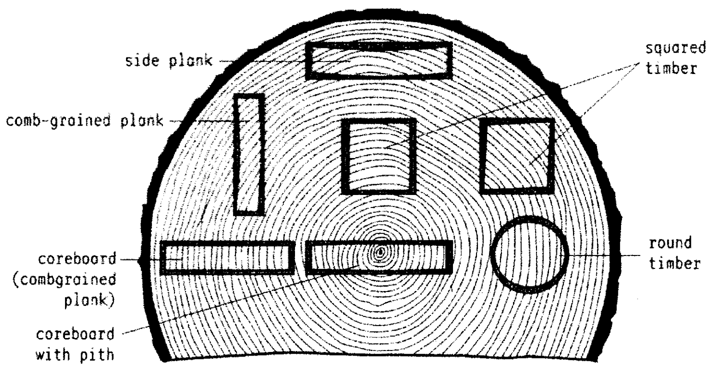


Figure 5 Types of Cut (Basics Timber Construction)

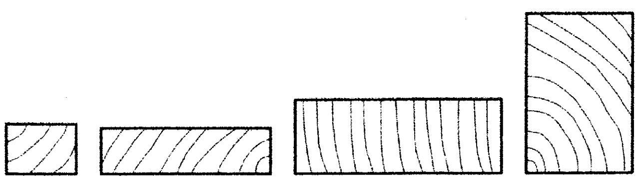


Figure 6 Cross Sections: lath, plank, board, squared timber (Basics Timber Construction)

Dimension

In addition to the types of cuts the timber industry has standardized finished lumber dimensions available for design. American standard timber sizes come in widths of 2, 2 ½, 4, 3 ½, 4, 4 ½ inches and heights of 2, 3, 4, 5, 6, 8, 10, 12, 14, 16 inches (Table 1). Dimensional lumber is the term given to finished lumber. Nominal lumber refers to rough lumber before it is finished and is usually larger than the actual dimensions. The lack in processing knowledge by a designer requires a timber fabricator to remodel all members of a 3-dimensional timber model for fabrication purposes. Knowledge in timber processing would reduce the amount of remodeling necessary in the design to fabrication process of timber structures (Carbone, 2010).

Cross sections for lath, plank, board, squared timber

	Thickness t	**Width w**
	Height h [mm]	**[mm]**
Lath	$t \le 40$	$w < 80$
Plank	$t \le 40$	$w \ge 80$
Board	$t > 40$	$w > 3d$
Squared timber	$w \le h \le 3w$	$w > 40$

Customary timber cross sections

Lath cross sections	24/48, 30/50, 40/60
Thicknesses for planks	16, 18, 22, 24, 28, 38
Thicknesses for boards	44, 48, 50, 63, 70, 75
Thicknesses for planks/boards	80, 100, 115, 120, 125,140, 150, 160, 175

Customary dimensions of squared timber

6/6, 6/8, 6/12, 6/14, 6/16, 6/18
8/8, 8/10, 8/12, 8/16, 8/18
10/10, 10/12, 10/20, 10/22, 10/24
12/12, 12/14, 12/16, 12/20, 12/22
14/14, 14/16, 14/20
16/16, 16/18, 16/20
18/22, 18/24
20/20, 20/24, 20/26

American timber sizes in inches

Widths	2, 2½, 3, 3½, 4, 4½
Heights	2, 3, 4, 5, 6, 8, 10, 12, 14, 16

Table 1 Lumber Dimensions

2.2 Systems in Timber Construction.

Log Construction

One characteristic of log construction (Figure 7) is the large amount of timber needed and the great degree of slump of the horizontally placed members. Typical timber construction joints are mortise and tenon as shown in section 3.3 between the horizontal trunks.

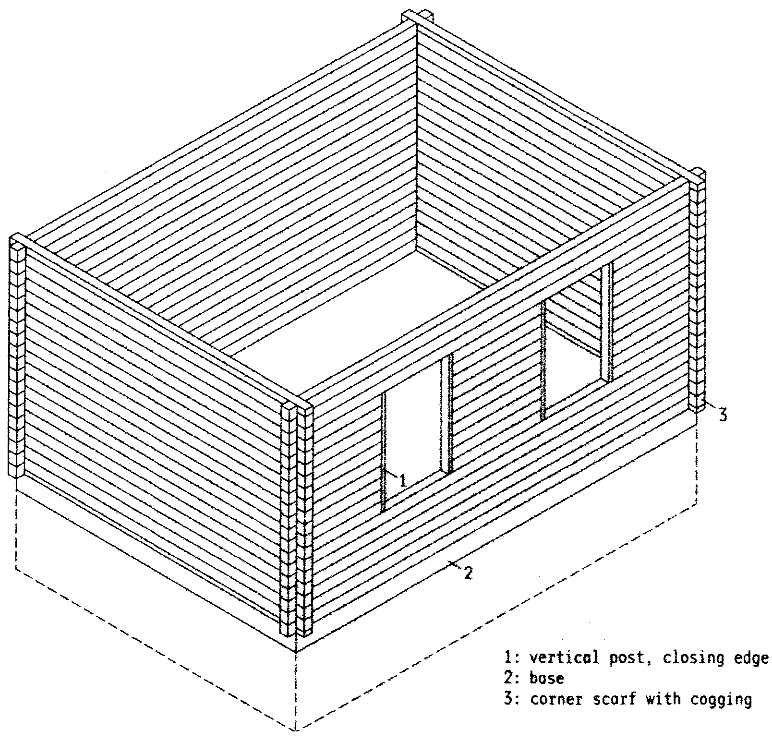


Figure 7 Log Construction (Basics Timber Construction)

Traditional timbered structures

Traditional Timbered construction is attractive because of the visible distinction between load bearing and non-loadbearing parts, between structural timbers and wall filling elements. One characteristic feature of timbered structures (Figure 8) is that the vertical posts, horizontal rails and diagonal braces are held together at the bottom by the threshold and at the top by the header.

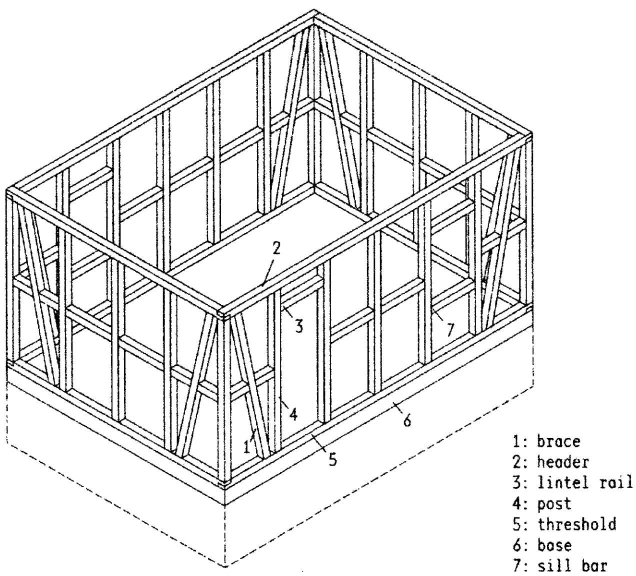


Figure 8 Traditional Timbered Structure (Basics Timber Construction)

Heavy Timber Construction

Heavy timber construction has long been recognized by the model building codes as fire resistant. To meet the requirements of heavy timber construction, limitations are placed on the minimum size, including depth and thickness, of all load-carrying wood members.

Timber frame construction

Timber frame construction also known as “balloon frame” (Figure 9) has the difficulties of placing high structural elements in position and problems with sound transmitted by the vertical members running through all the stories of a building. This building method uses wall elements assembled as frames lying on the ground raised into position when erecting the building.

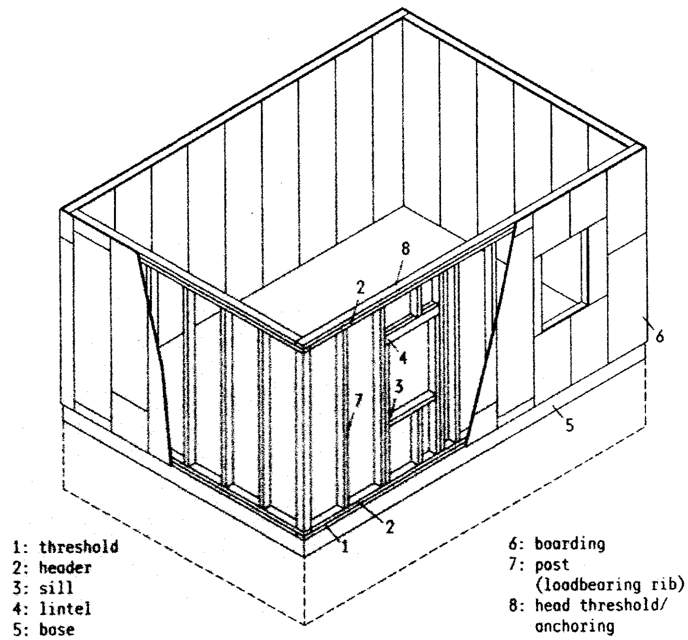


Figure 9 Timber Frame Construction (Basics Timber Construction)

Skeleton construction

Skeleton construction (Figure 10)was developed because of a desire for more freedom in dividing up space and for larger areas of glazing. The walls forming a room are erected independently of the loadbearing skeleton making it possible to include large areas of façade glazing. The loadbearing skeleton remains visible inside or outside. Laminated timber in skeleton construction makes large spacing between support structures possible.

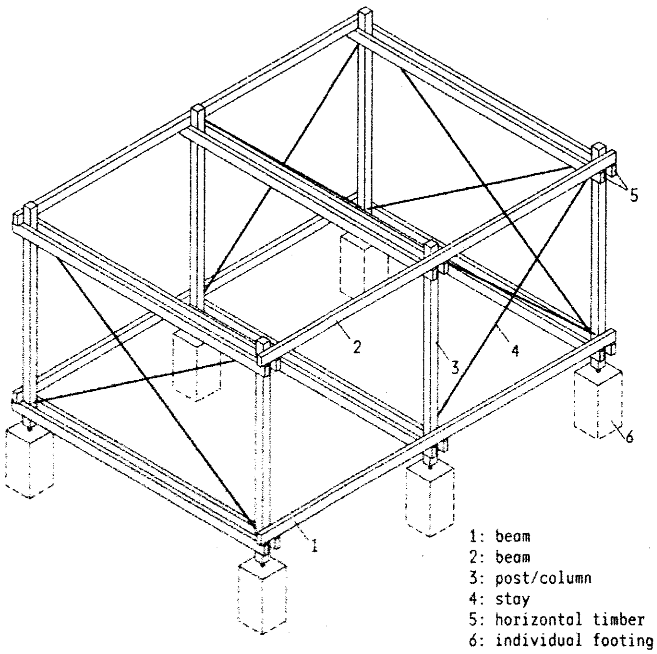


Figure 10 Skeleton Construction (Basics Timber Construction)

Laminated Timber Construction

Specially graded laminations with high strength and stiffness properties create glulam members with exceptional structural properties. The highest grades of lumber are used in areas of greatest stress, with lower grades used where strength is not as critical. In a typical glulam bean, stresses are highest near the top and bottom of the member, so the highest grades are placed near the surfaces, with lower grades placed in the core. The high strength and stiffness of laminated timbers enable glulam beams to span large distances without intermediate columns (AITC American Institute of Timber Construction, 2010). Disadvantages of using laminated timber include high-cost, complex connections required and increased labor time in fabrication and installation.

2.3 Case Studies

Centre Pompidou-Metz

Designed by architect Shigeru Ban, Tokyo & Jean de Gastines, Paris and Phillip Gumuchdijan of London, Centre Pompidou-Metz is located in the city of Metz, France 3 ½ hours east of Paris. The building reaches 7 meters high with a surface area of 8,000 m2. The roof structure is composed of two layers of continuous glue laminated timber (Figure 11) assembled from almost 1800 pieces resembling the canework pattern of a Chinese hat. The laminated timber is highly resistant and enables each spline to span uncommon lengths of 40 meters, resting on only a few points of support. The structure is covered with a waterproof membrane from fiberglass and Teflon (PTFE or Poly-Tetra-Fluoro Ethylene).

The construction of this project required digital expertise from Switzerland based firm Designtoproduction and timber construction company Holzbau Amann. Designtoproduction helped generate reference geometry of the roof and provided the timber construction company with necessary CAD tools to efficiently define, detail, and produce each doubly curved wooden glulam segments (Figure 11) from a parametric model. Each glulam lath is nominally a 6" x 18" glulam, developed over the complex surface and joined by a unique pin at each intersection.

The translation of geometry to machine code was accomplished with common CAM tools and a lot of manual work. Fabian Scheurer of designtoproduction says, " there is no out-of-the-box CAM software that can deal with the complex machining necessary to achieve an optimal result for components like those found in Centre Pompidou-Metz" (Scheurer, 2010).

Figure 11 Centre Pompidou-Metz (Structurae)

Expodach

Expodach is a large-scale roof structure located in Hanover, Germany designed by architect Thomas Herzog. Hanover's Expo-Dach (Expo-Roof) symbolizes, a partnership between man, nature and technology. This timber structure is made of a curving roof supported by forty massive columns promoting the use of timber as a raw material. Each tree stem column is roughly twenty meters high, splayed apart like mooring piers. Each stem is cut from more than 200-year-old fir trees in the southern Black Forrest (Figure 12). Each column, like all the timber used on the project have been left in a natural untreated state, with only the occasional split and their deep red color as decoration.

The large roof structure consists of ten individual canopy elements each roughly 40 x 40 m in size, covering a total area of 16,000m2 at a height of more than 20m. The loads from the lightweight double-curved lattice shells are transmitted to powerful central structures assembled from the trunks of trees.

The constant quality and moisture controls, to which the tree stems were subject played a crucial role in this project. Ultrasonic tests were carried out before the trees were cut. Measurements were made by the Institute for Timber Structures of the Ecole Polytechnique Federale de Lausanne (EPFL) to determine the timber quality of the trees while still standing. This ultra-sonic technique helps determining if a tree has heart rot since the sound waves have to travel a greater distance around the rotten sections. The removal of 50-meter trees from the forest allowed room for new growth. In this way, the forest can be rejuvenated without clear cutting whole areas.

The architects and engineers also had to decide where solid timber members, glued laminated timbers and laminated wood sheeting could be used most effectively, optimally exploiting the specific characteristics of these materials according to structural, processing and environmental criteria. The construction of the lattice shells involved only a small amount of prefabrication. They were assembled on seven large centering structures immediately adjoining the site. Machines coupled to computer numerically controlled (CNC) systems were used to produce the individual structural elements. With the use of CADWORK® it was possible to generate and develop a list of building elements transferred to a 5-axis CNC machine ensuring the necessary precision (Herzog, 2000).

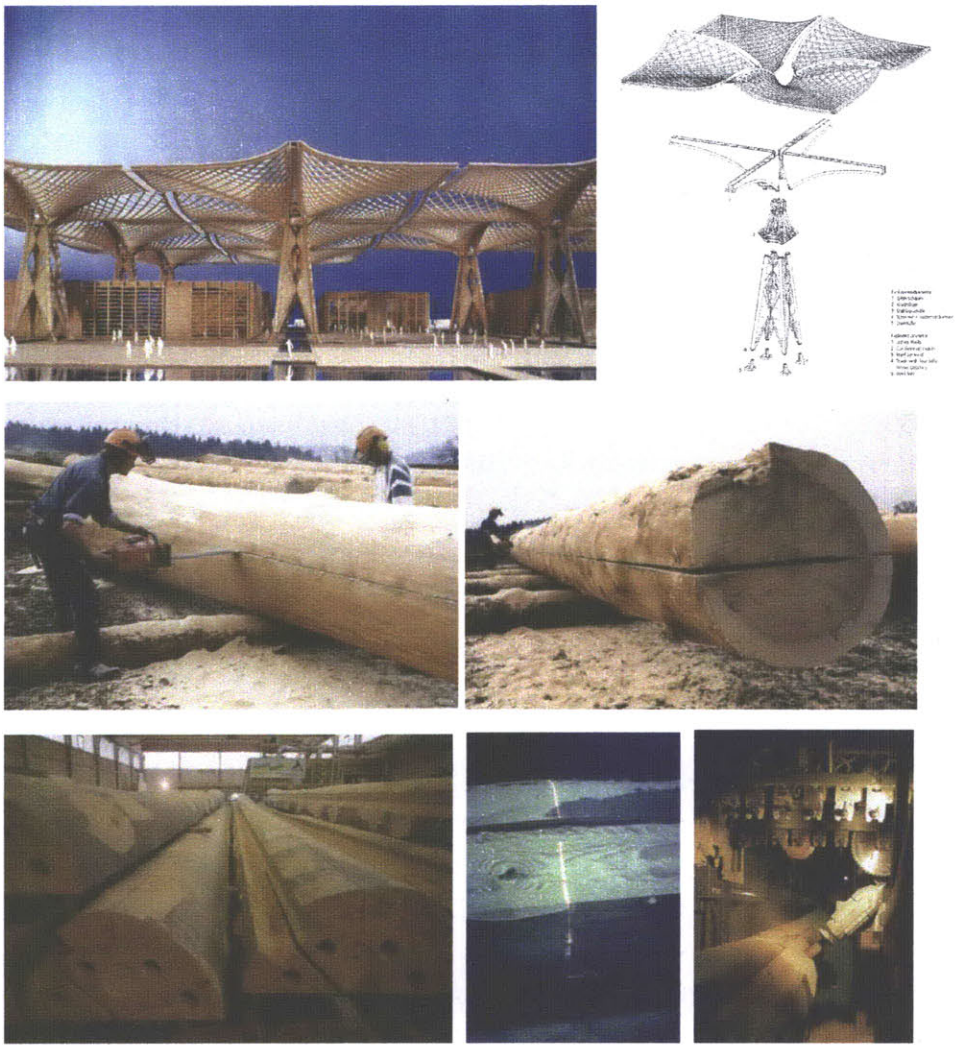


Figure 12 Expodach (Expodach)

2.4 Interviews

Blumer-Lehman

Blumer-Lehman AG is a timber company intensely engaged in wood. Blumer-Lehman has been building for over 135 years. Design, planning, production, supply, installation, service and maintenance are the company's core competences. With the aid of parametric modeling and digital workflows between digital data and 5-axis CNC joinery machines, Blumer-Lehman is able to build free-form surfaces.

During a workshop on contemporary timber construction sponsored by the (ETH) Eidenossishe Technishe Hochschule Zurich, I had the opportunity to visit their facilities and learn their process first-hand. The construction of timber structures begins with the delivery of raw timber material to their facilities. The raw material is passed through a series of machines where it is laser scanned, cut using optimization software, planed smooth, catalogued and set to dry for future use (Figure 13). All the waste material is compressed into blocks, burned and used as fuel to run the mill.

Figure 13 Blumer-Lehman Sawmill Zurich, CH images from video taken of mill process

Benson Wood

Bensonwood is a timber company found in New Hampshire specializing in the design and construction of panelized, prefabricated, high-end modular timber frame homes and complex heavy timber structures. Bensonwood is made up of engineers, architects, framers, and carpenters capable of 3d modeling and CNC integration.

Bensonwood generates 3d models followed by detailed shop drawings using the latest CADWORK® software. The use of computer modeling allows them to create timber and panel takeoffs or bill of materials for more accurate cost estimating prior to contracting. The model is also used in the generation of shop drawings, joinery detailing and specification for timber species and grade.

The CNC, computer numerically controlled integration by Bensonwood utilizes the German-built Hundegger cutting machinery. Customized to be integrated with their CADWORK® software, the Hundegger is capable of cutting timber up to 50 feet in length and creating joinery details with tolerances of 1/32 of an inch in one operation, quickly and affordably.

During a visit to their facilities I had the opportunity to take a guided tour by structural engineer Chris Carbone. Chris walked me through their facilities and shared Bensonwood's process for the delivery of a timber construction project. As Chris explained, the process typically begins with an architect's design drawings. Bensonwood takes an architect's drawings and build a 3d model using their CADWORK® software where they engineer all the joint details between timber members and generate the machine code used for the Hundegger. When asked why they had to remodel from architectural drawings and not just use a 3d model produced by the architect Chris responded with "Architects do not always use solid modeling software required to build their joint details. Architects are not always familiar with modeling the tolerances required for their machines and currently there is no way to assure the machine code generated from the design would be accurate" (Carbone, 2010). The timber elements pre-fabricated at their facilities are then taken on-site to be assembled.

2.5 Shipbuilding

Hulls are characterized by relatively round body sections, in which the majority of the component frame timbers are curved (Figure 14), and by complex framing systems frame elements are connected to each other in a variety of ways to make up the hull shape of a ship. Timber selected for its curvature (Figure 15) was not cut short rather it was used in full. The sharper the curve, the harder it is to find timber that follows the radius of the curve.

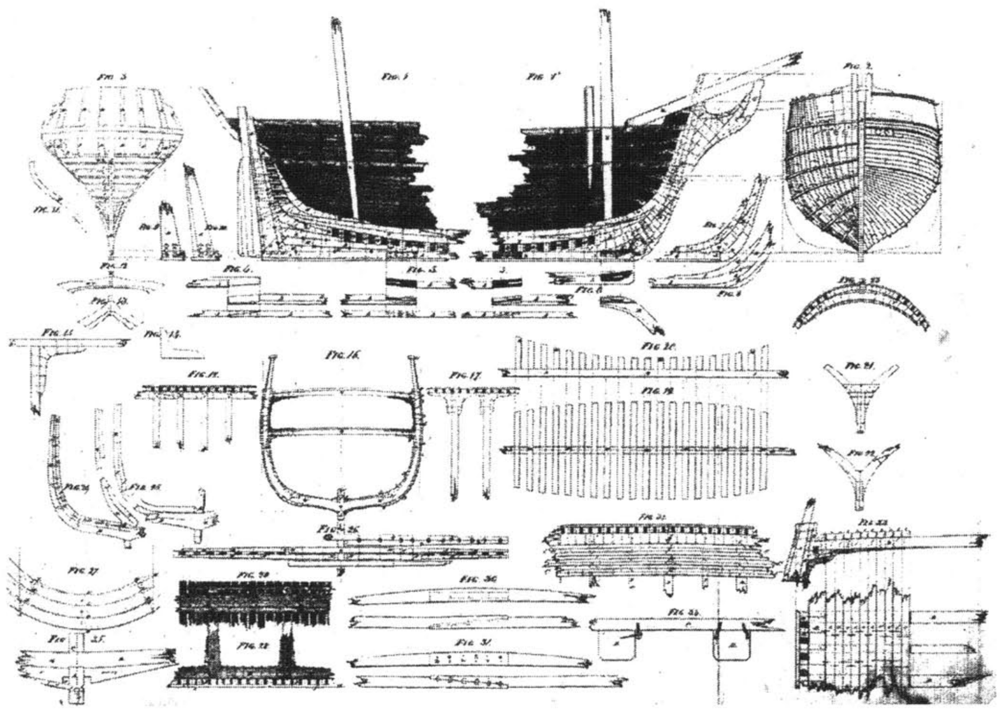


Figure 14 Wooden Ship Drawing (Ships, Innovation & Social Change: Aspects of Carvel Shipbuilding in Northern Europe)

Timber of Different Curvature

Naturally curved timber in architecture is used in curved braces and tie beams

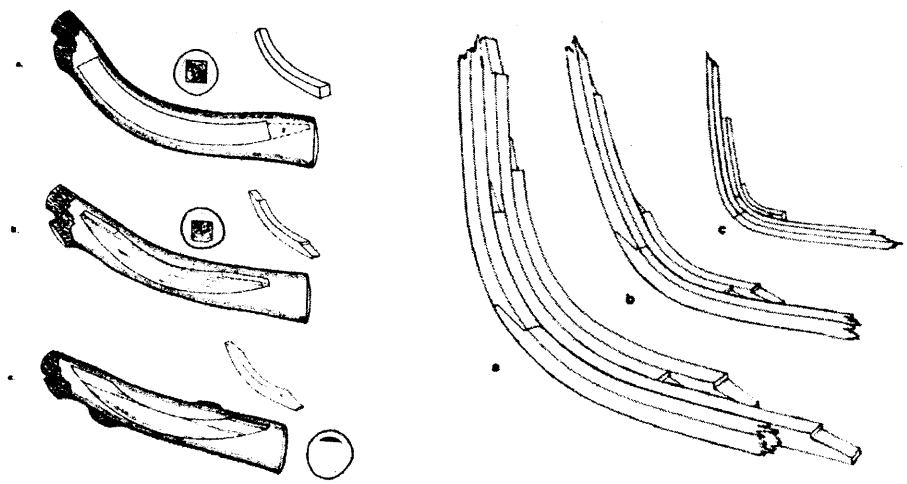


Figure 15 Timber Curvature Used in Ship Hull (Ships, Innovation & Social Change: Aspects of Carvel Shipbuilding in Northern Europe)

2.6 Pioneers of Natural Architecture

There is an emerging art movement that explores mankind's desire to reconnect to the earth, through the built environment referred to as 'natural architecture'. Natural architecture aims to create new, more harmonious, relationship between man and nature by exploring what it means to design with nature in mind.

In the book title Natural Architecture the author Alessandro Rocca says " We see nature today as a universe in rapid mutation. Today's naturalism is dominated by the effects of scientific progress". The roots of this movement can be traced back to earlier artistic shifts like the land art movement of the late nineteen sixties where new appreciation of nature in all forms of art and design were developed. Natural architecture aims to capture the harmonious connection we seek with nature by merging humanity and nature through architecture. These structures deliberately expose the natural materials used in the building process (Rocca, 2007).

Tunnel with Nature

Tunnel with nature (Figure 16) was built in 1996 by designers Gilles Bruni and Marc Babarit using willow boughs and branches.

Figure 16 Tunnel with Nature (Natural Architecture)

Willow Cathedral

Willow cathedral (Figure 17) was built in 2001 spanning 800 square meters and reaching 15 meters in height designed by Marcel Kalberer from willow trees.

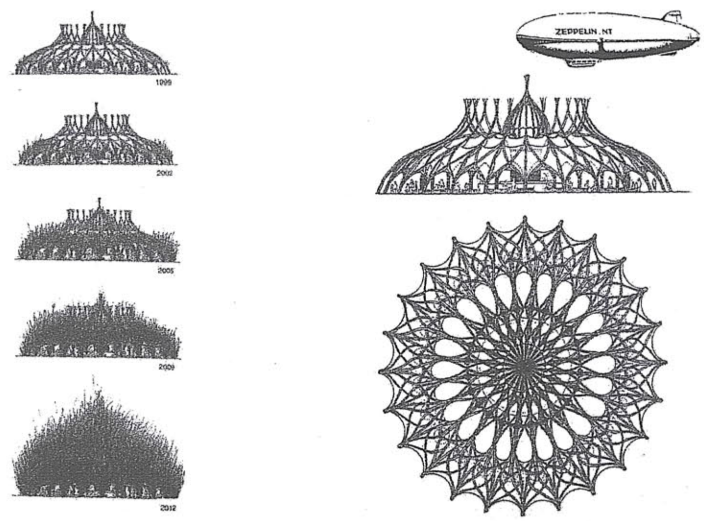


Figure 17 Willow Cathedral (Natural Architecture)

Canopy

Canopy (Figure 18) is a more recent project designed by nArchitects for an installation for MoMA/P.S.1 Young Architects Program in 2004 from bamboo poles spanning 11,000 square feet.

Figure 18 Canopy (Natural Architecture)

Fab Tree Hab

Fab Tree Hab (Figure 19) by Terraform proposes an ecological design of a living prefabricated home. This home design is intended to replace the outdated design solutions and proposes a method to grow homes from native trees and plants. This living structure is grafted into shape with CNC reusable scaffolds.

Fab Tree Hab introduces pleaching. Pleaching is a method of weaving together tree branches to form living archways, lattices, or screens. The trunks of inosculate, or self-grafting, trees, such as Elm, Live Oak, and Dogwood, are the load-bearing structure, and the branches form a continuous lattice frame for the walls and roof. Prefab scaffolds cut from 3d computer files control the plant growth in the early stages. This project proposes the use of mixed traditional prefab construction with living materials.

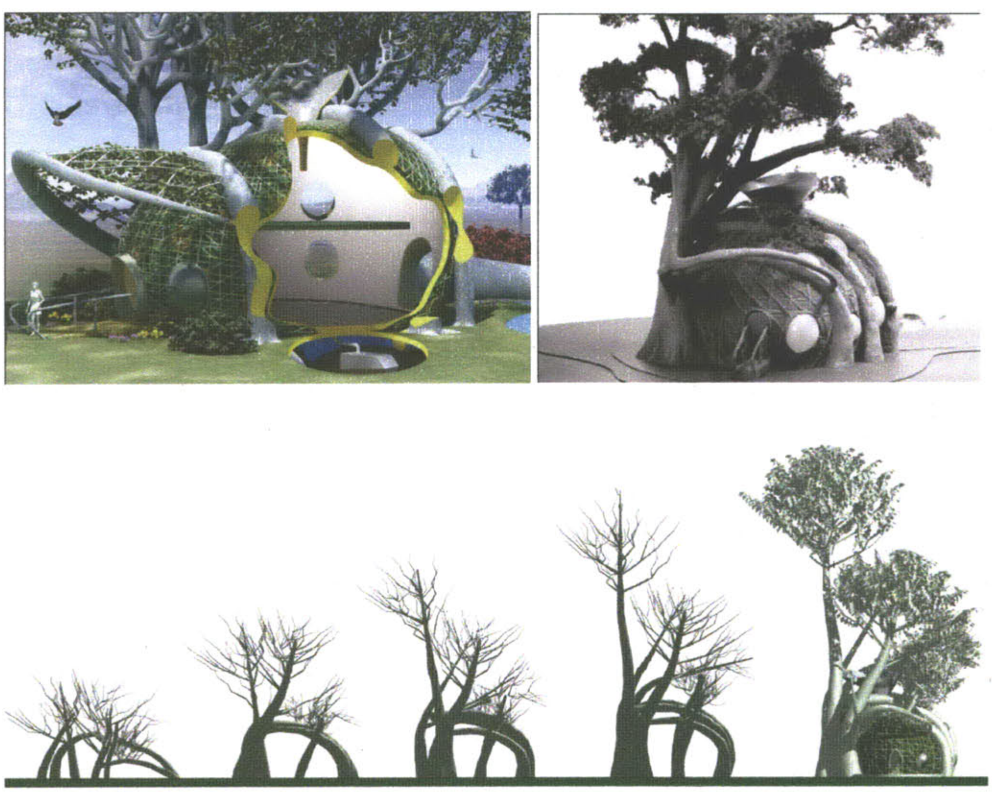


Figure 19 Local Biota Living Graft Structure (FAB TREE HAB, Terraform)

2.7 Grafting

Grafting is an interesting way of thinking of new joining methods in timber construction. Fab Tree Hab introduces the notion of pleaching as a method of weaving together tree branches allowing tree branches to self-graft into a continuous lattice frame for the walls and roof of a structure. Below are a few examples of grafting methods found in Botany taken from research at the University of Missouri and the North Carolina State University College of Agriculture and Life Sciences.

Bark Graft

Bark grafting (Figure 20) is used primarily to top work, this technique can be applied to rootstock of larger diameters and is done during early spring when the bark slips easily from the wood but before major sap flow.

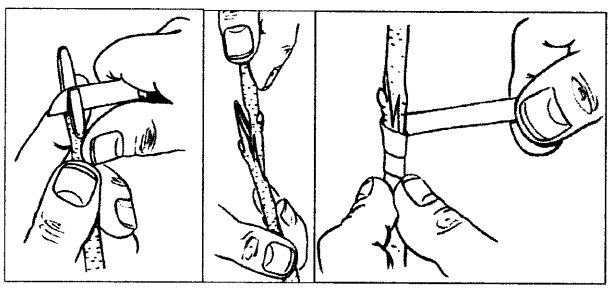


Figure 20 Bark Graft (University of Missouri)

Cleft Graft

Cleft grafting (Figure 21) is one of the simplest and most popular forms of grafting. Cleft grafting is a method for top working used to propagate varieties that are difficult to root. This type of grafting is usually done during the winter and early spring.

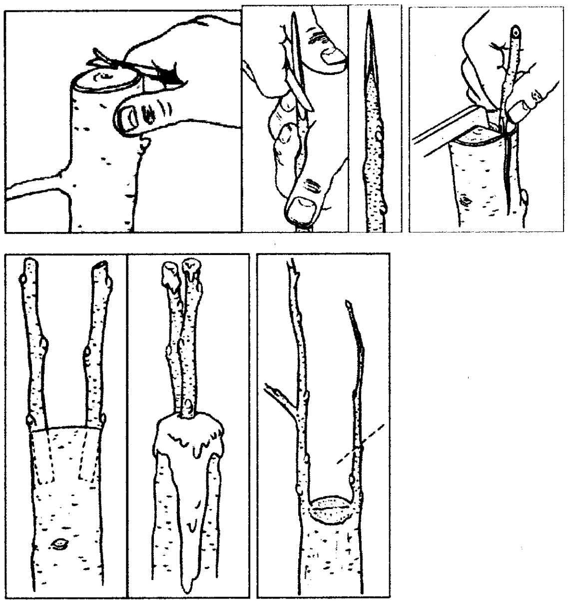


Figure 21 Cleft Graft (University of Missouri)

Saddle Graft

Saddle Graft (Figure 22) is relatively easy to learn, used in mid-to late winter. Both rootstock and scion should be the same diameter.

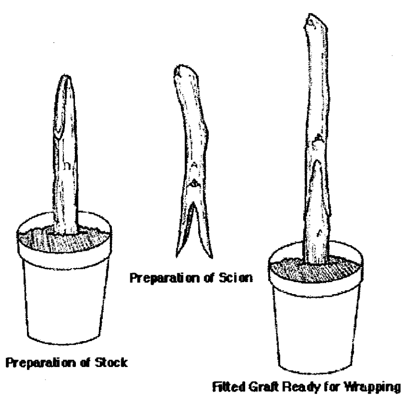


Figure 22 Saddle Graft (North Carolina State University College of Agriculture and Life Sciences)

Side Veneer Graft

Side veneer grafting (Figure 23) is the most popular way to graft conifers, especially those having a compact or dwarf form. Side-veneer grafting is usually done on potted rootstock.

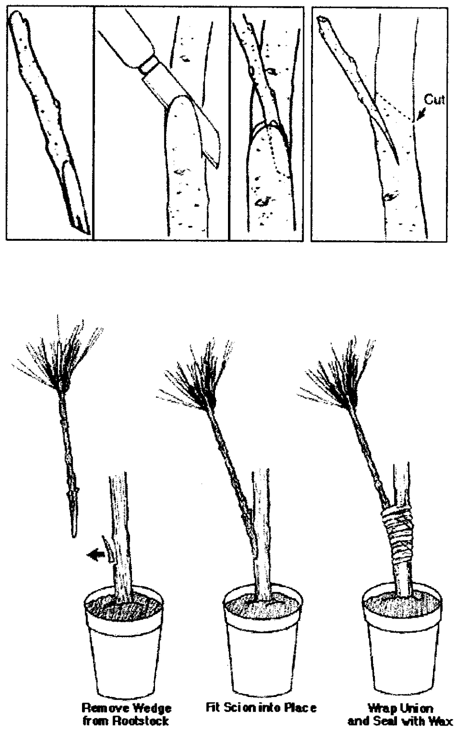


Figure 23 Side Veneer Graft (North Carolina State University College of Agriculture and Life Sciences)

Splice Graft

Splice grafting (Figure 24) is used to join a scion onto a stem of a rootstock or onto an intact rootpiece. This method is applied to herbaceous materials that callus or knit easily. In splice grafting both stock and scion must be of the same diameter.

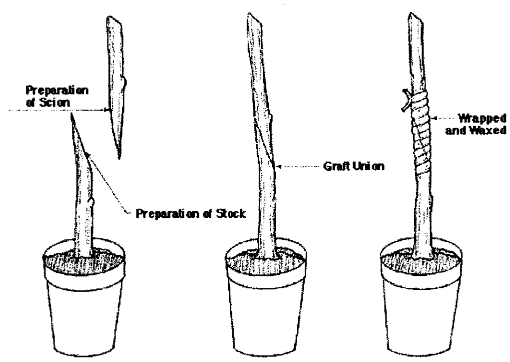


Figure 24 Splice Graft (North Carolina State University College of Agriculture and Life Sciences)

Whip and Tongue Graft

Whip and Tongue grafting (Figure 25) is used to graft nursery crops. Both rootstock and scion should be of equal size. This technique is similar to the splice grafting.

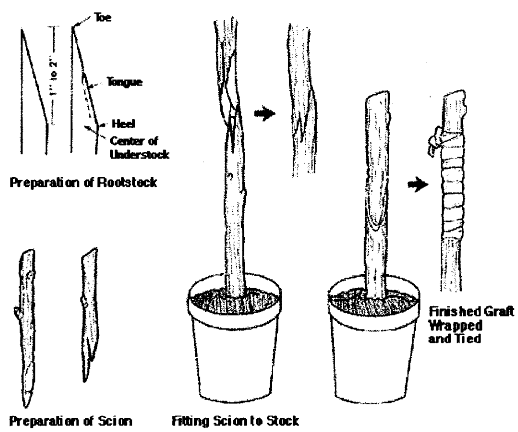


Figure 25 Whip and Tongue Graft (North Carolina State University College of Agriculture and Life Sciences)

3 Digital Tools

3.1 Building Information Modeling (BIM) in the Timber construction Industry

Today, the use of digital modeling technologies and building information modeling in the design and construction of timber structures is ubiquitous. The GSA U.S General Service Administration defines Building Information Modeling (BIM) as the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility at a recapitalized (modernized) facility. The resulting Building Information Model is a data –rich, object based, intelligent and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback and improvement of the facility design (U.S. General Services Administration Public Buildings Service Office of the Chief Architect, 2007).

BIM involves representing a design as objects. The geometry may be 2D or 3D but composed together these objects define a building model. When an object is change or moved, BIM design tools allow the extraction of different views from a building model for drawing production and other uses. Having this drawing consistency eliminates many errors. Modern BIM design tools define objects parametrically. Objects are defined as parameters and relations to other objects with parent-child relationships that allow changes to propagate throughout a building model. Parametric objects automatically re-define themselves according to the rules embedded.

Chuck Eastman in his book titled "BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors", writes why BIM is important. "BIM is important because 3D objects are machine readable and spatial conflicts in a building model can be checked. Because of this capability, errors and change orders are greatly reduced". BIM models can provide cost estimates, material tracking and ordering for the construction of a building. Eastman also writes " BIM can beneficially impact all parties in the construction process similar to the automation of manufacturing in the 1980s, when most manufacturing industries first adopted 3D modeling and digital representations" (Eastman, Teicholz, Sacks, & Liston, 2008).

According to "The Business Value of BIM: Getting Building Information Modeling to the Bottom Line SmartMarket Report" published by McGraw Hill Construction, almost 50% of the industry is now using BIM. All BIM users plan significant increases in their use. The vast majority is experiencing real business benefits directly attributed to BIM.

Future opportunities for adopting BIM include better-designed projects, lower risk and better predictability of outcomes, prefabrication of larger, more complex parts of projects, reduced claims, disputes and conflicts. Also published in the SmartMarket Report, as BIM reduces conflicts and creates confidence, many team members see opportunities for value in fabrication. Accurate fabrication of materials reduces waste while preassembly can save time (McGraw Hill Construction, 2009).

Specifically, the use of BIM in the design and construction of timber structures is ubiquitous but suffers many setbacks in streamlining the process from design to fabrication. Expert knowledge is required to facilitate in the translation of digital data to machine code. Software in this industry is very specific and often lacks the ability to describe complex geometries for fabrication, therefore requiring customization from project to project.

CADWORK

CADWORK is a CAD/CAM system specially tailored to the demands of timber/log construction that provides a fully integrated solution for all stages of design and fabrication. This software is widely used by both architects and engineers working on timber structures. This software allows for straightforward rectangular or curved sections to be modeled within a 3d modeling environment. This software aides in automating joints from timber to timber and aids in the generation of machine code used in fabrication.

3.2 Digital Fabrication Technologies

As ubiquitous as digital modeling technologies, and now building information modeling in the timber construction industry has become, so has the use of digital fabrication tools in the automation of joint assemblies. Part modeling in computer-aided design applications can be traced back to the 1950s and 1960s when the first CAD/CAM systems were being developed. Shah and Mäntylä, in Parametric and Feature-Based CAD/CAM outline the four areas that have influenced CAD modeling as we know it today; NC machines first introduced in the early 1950s at MIT, sculpted surface modeling primarily in the aerospace and automobile industries, computer graphics technology and 2-dimensional systems used in drafting and detailing and engineering analysis based on finite element method (FEM. Early CAD systems were directed at drafting initially providing 2D drawing functions (Shah & Mäntylä, 1995).

During the late 1960s and early 1970s a desire to extend the 2-dimensional CAD systems to 3-dimensions emerged. Today's CAD modeling environments can be categorized into five categories: graphical modeling, surface modeling, solid modeling, parametric modeling and feature-based modeling. Not all of these digital environments support connections directly within computer-aided manufacturing environments (Schodek, Bechthold, Griggs, Kao, & Steinberg, 2004).

Computer Numerical Control (CNC) Technologies

The development of servomechanism control and a standardized numerical control language in the early 1950s lead the development of NC machine tools in parallel to digital computer technologies and established the basis for today's CNC technologies used in field of production (History: MIT Servomechanisms Laboratory: Institute Archives & Special Collections: MIT, 2010.).

Numerical control technologies allow automated equipment to be controlled and operated in real-time through the use of a symbolic language. Coupled with computers, CNC is at the heart of computer-aided manufacturing industries, as well as robotic manufacturing.

In the book titled "Digital Design and Manufacturing", Bechthold and Schodek outline some basic shared characteristics of CNC technologies to include the following: The preparation of instructions describing the work to be done in a digital format, reading those instructions via a controller, which "decodes" the instructions to convert them from a digital format to a stream of electrical impulses (Schodek et al., 2004).

Automatically Programmed Tools (APT) language was developed for NC in 1959 and announced by MIT in 1962 ("History: MIT Servomechanisms Laboratory: Institute Archives & Special Collections: MIT," n.d.). Many CNC tools are designed to make flat outline shapes and move primarily in the x and y axes, with limited control of the tool head in the z-axis. Shapes with complex solid geometries can be created using a variety of CNC tools. Milling machines, machining centers, lathes, drills, routers, and grinding machines can work directly on real building materials by reducing large pieces of stock to smaller finished pieces. The most common CNC machine is the three-axis mill. For shapes that require undercuts, more axes of movement may be added.

Bechthold and Schodek describe the steps necessary to send part programs to a CNC as: a digital design is produced within the CAD portion of a CAD/CAM program using Cartesian coordinates to create geometry (Schodek et al., 2004). A toolpath is defined within the CAD/CAM software that will produce the desired shape using the previously created geometric model. The toolpath is post-processed by the CAM portion of the CAD/CAM software to produce a G-Code or similar text file. The part program file is sent to the controller. The toolpath may be visually verified on screen and modified to suit the parameters of the specific machine tool. As the part program is read by the controller, the instructions written in a symbolic language are converted into a digital format to communicate with motors or other actuators that make the tool move. The machine tool is then commanded to run the program. At which point, the translated toolpath commands are sent to the tool itself and it begins to do its work.

CAD/CAM processes require digital designs from CAD environments to CAM environments be verified to make sure the file transferred is accurate. Parameters must be checked to ensure the design can be manufactured using available tooling and the manufacturing methods must be compared to find most appropriate methods for completion. Bechthold and Schodek write, "As CAD/CAM software continues to be developed, much effort is being made to embed logic and knowledge based procedures within the software itself to expedite the making of objects" (Schodek et al., 2004).

Hundegger

Hundegger is one of the most widely used joint automating machines in the timber industry. Hundegger located in Hawangen, Germany with a partner office in Charleston, UT sells and services Hundegger Machines. Hundegger machines (Figure 26) are used in the timber industry to automate joinery in lumber and timber members. The five-axis CNC milling Hundegger machines are equipped with Single-Piece-Construction-Program (SPCP) software. SPCP allows job files to be exported from major design, joinery and CAD programs. The SPCP software offers advanced lumber/timber optimization of stock timber sizes, 3d display with selectable views, simulation of all processes and operations, creates saw lists, production lists, and rough cut lists.

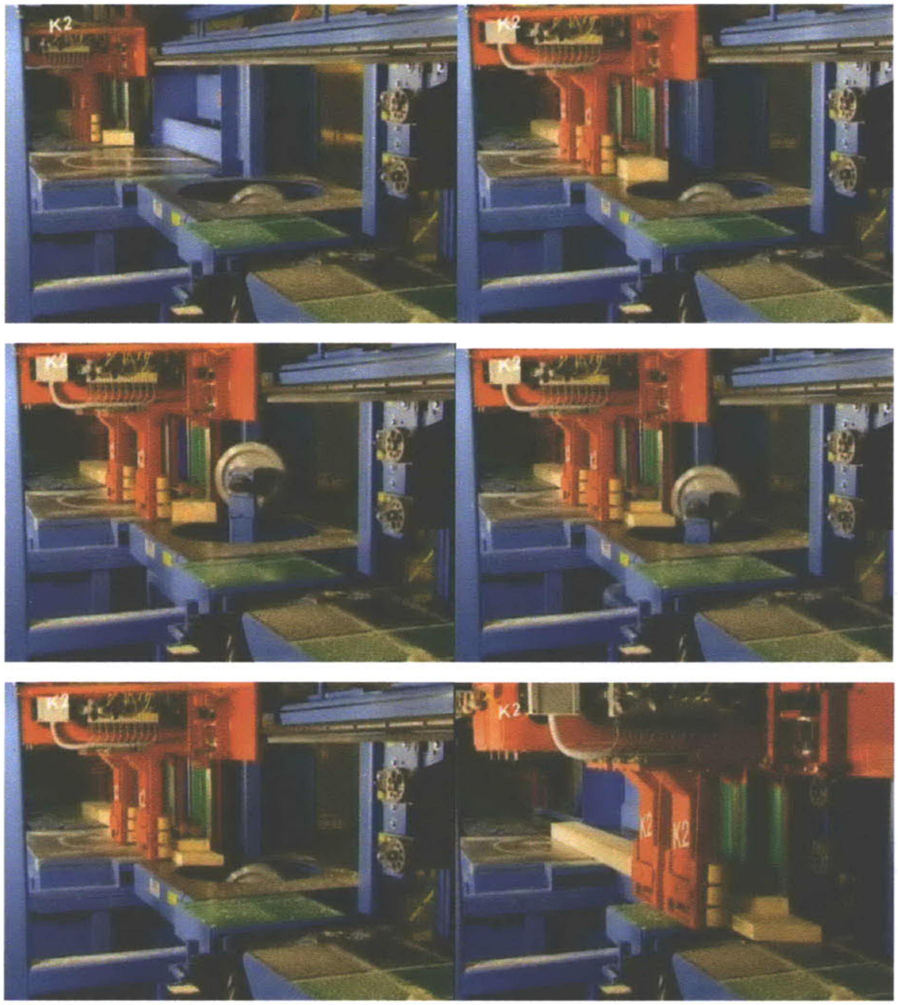
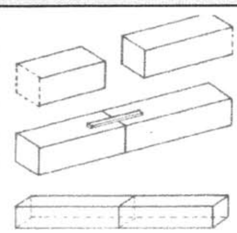
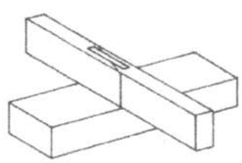
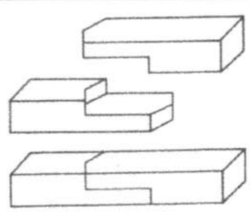
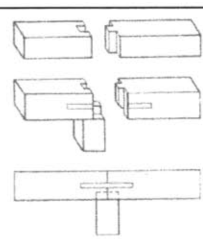
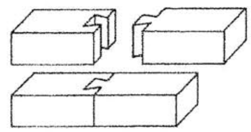
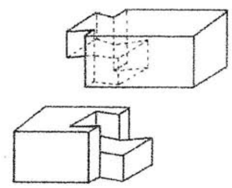
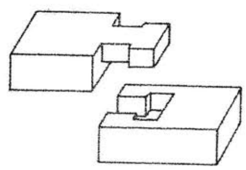
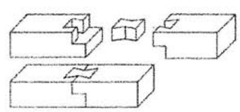
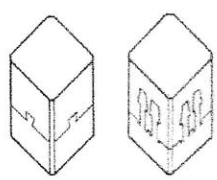


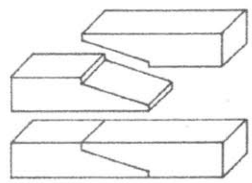
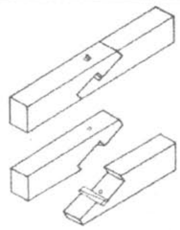
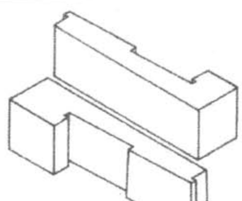
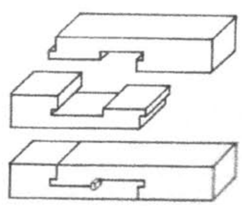
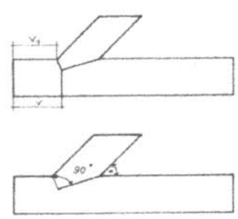
Figure 26 Hundegger K2 (Hundegger AG) Machine Operation Video Sequence

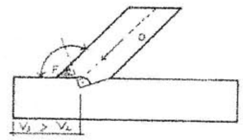
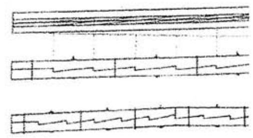
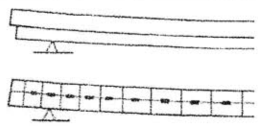
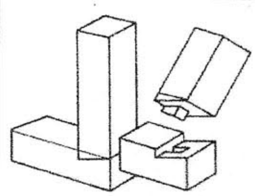
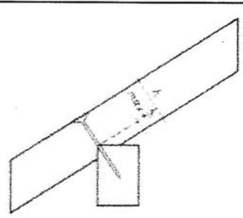
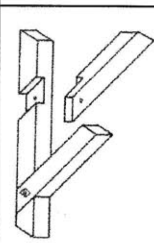
3.3 Joint Typologies

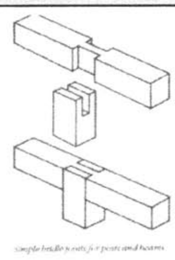
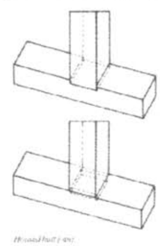
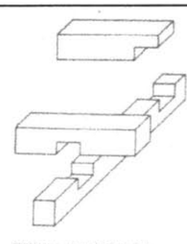
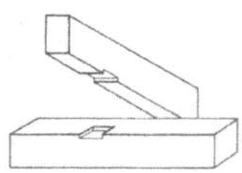
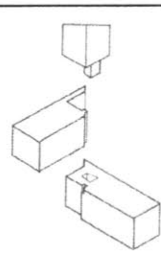
Joints in timber construction play a crucial role in the design and construction if timber structures. In a book titled "Encyclopedia of Wood Joints" by Wolfram Graubner, Graubner describes the different families of wood joints found in timber construction and the methods for their implementations (Graubner, 1992). Essentially, there are four kinds of joints found in timber construction including splicing joints, oblique joints, corner and cross joints, and edge joints.

Splicing Joints	
Butt Joints	 Simple butt joint
Splayed Joints	 Simple splayed joint
Lapped Scarf Joints	 Half-lapped V joint
Mortise and Tenon Joints	 Mortise and tenon

Dovetail Joints	 Through dovetail
Double dovetails	 Double dovetail joint
Gooseneck joints	 Simple gooseneck joint (Kama tsugi)
Loose tenons and keys	 [illegible]
Four Way joints	 Double dovetail cut diagonally

Tabled Splayed Joints	 *Simple splayed scarf joint*
The Gerber Joint	 *Variations of the Gerber joint*
Tabled Lap Scarf Joints	 *Lipped tabled lap scarf*
Tabled Joints with Wedges	 *Wedged lipped tabled lap joint (Kane-gata-ai-gaki-tsugi)*
Oblique Joints	
Notched Joints	

Shouldered Heel Joints	 Slope-shouldered heel joint
Toothed Beams	
Splined Beams	 Unattached beams (top) and splined beam, stronger and deflects less.
Right angles notched joints	 Notched corner post joint with offset shouldered tenon
Birds Mouth Joints	 Bird's mouth joint on a common rafter
Angled Lap Joints	 Angled lap joint

Corner and Cross Joints	
Bridle Joints	
Butt Joints	
Lap Joints	
Cogged Joints	
Tongue Joints	

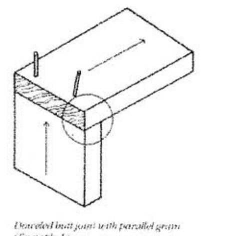
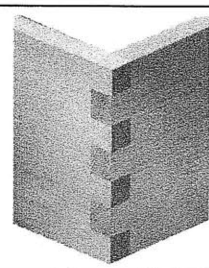
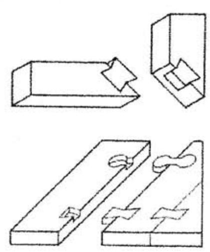
Carcase Joinery	
Finger Joints and Dovetails	
Edge Joints	
Butterfly Key	

Table 2 Joint Typologies

3.4 Enabling Digital Design To Fabrication Workflows

To understand how to enable digital design to fabrication workflows, it is important to understand how building components are created. In Autodesk's white paper BIM and Digital Fabrication the authors describe how structural steel components that make up a building's frame are created (Autodesk, 2008). First a steel mill uses a hot-rolling manufacturing process to create stock structural steel members. This stock material is purchased by steel fabricators who cut and prepare the sock structural beams and columns for building construction based on shop drawings—instructions that describe exactly how to fabricate each individual piece of a structure. Once they are fabricated, the steel members are shipped to the building site and put in place by steel erectors.

Structural drawings contain only general requirements for steel fabrication. A steel detailer then takes those construction drawings and applies those general connection instructions to the specific structural components and the specific geometry of the building as represented in the construction drawings, creating shop drawings that instruct the steel fabricator exactly how to fabricate each piece of steel in the building. Shop drawings include detailed information pertaining to material specifications, sizes, dimensions, welding, bolting, surface preparation, painting requirements, etc.

Shop drawings are either manually created with drafting software or created with special steel detailing software. Prior to the release of the shop drawings for fabrication, the structural engineer checks each one to verify that the information matches the structural design. Steel fabricators generally use CNC beam line machines that automatically cut and drill a beam. Some fabricators hand program the CNC machine based on the information from the shop drawing. Other fabricators use the digital fabrication models to automatically program the machine.

3.5 Extending BIM to Fabrication

Complex models require the use of complex modeling environments able to generate instructions specifying tool movement related to the geometry of an object. Once toolpaths are determined and parameters are defined, the CAM software will create a file. In some cases the file is proprietary and is stored along with the drawing file to be post-processed at a later time. In other cases the post-processing for a specific tool is immediate, resulting in a file that may be sent to a machine.

As CAD-based models in manufacturing can feed the manufacturing process, a building information model can feed the fabrication process. Design information can be exported for use in fabrication. The source of information used in the detailing and fabrication is based on highly accurate, coordinated and consistent building information model. In a book titled Dimension: 306090 12 Fabian Scheurer of designtoproduction says, “To efficiently create complex form from standard materials, the information (complexity) must be handed down the production chain seamlessly, which creates a certain effort. This effort can be minimized through parametric and digital fabrication methods” (Abruzzo & Solomon, 2008).

An advantage of using BIM in the supply chain is the ability to manage cost. Using the design model directly for fabrication brings fabrication considerations forward in the design process. Important to digital design-to-fabrication process is to form collaboration between designer, detailer and fabricator. The link is facilitated by collaborative practices and alternate delivery approaches. Steps that were once sequential can be done concurrently. The design model and shop drawings can be created in tandem.

3.6 Towards Distributed Fabrication

Through advanced technologies, fabrication is becoming ubiquitous. In an article published by wired magazine titled “In the Next Industrial Revolution, Atoms are the New Bits”, Chris Anderson editor in chief of wired says,“ In the age of democratized industry, every garage is a potential micro-factory, every citizen a potential micro-entrepreneur”. Through out his article he outlines the steps necessary towards building the dream as 1. Invent, 2. Design, 3. Prototype, 4.Manufacture, 5.Sell (Anderson, 2010).

4 Registered Bits in Timber?

What is it that our materials compute? Specifically, what are the bits of information registered within timber? In this universe made of bits how do we use this information for design?

In "Design in Nature" Mattheck says timber continuously computes the following three instructions for growth as: apical dominance, geotropism and phototropism. The material behaviors of timber also process information. Stiffness and strength vary as a function of orientation between longitudinal, tangential, and radial directions. The interactions and processes of information that occur within this material happen at the molecular level during growth and at the macro level when applied under load-bearing conditions. The capacity to bear loads becomes a function of density of wood, type of cut, type of construction method and amount of defects contained in the material.

How do we use this information for design? is a meaningful question because the timber construction industry has engineered multiple systems of construction. Each system for construction is most appropriate for different design intentions and most of the time for complex geometrical buildings they have to be mixed and match. To think of future design solutions an understanding of the material would be necessary. The case studies studied here are good examples of projects with some understanding of materiality and use the affordances found in wood.

In the Centre Pompidou-Metz the roof structure is composed of laminated timber assembled from 1800 unique pieces. The laminated timber enables each spline to span uncommon lengths of 40 meters. Each unique joint includes a pin at each intersection. Custom digital tools were required for the design to fabrication processes. This construction system used the affordances found in the material.

In Expodach the curving roof, is supported by forty massive columns promoting the use of timber as a raw material. Loads are transmitted to powerful central structures assembled from the trunks of trees and the architects and engineers had to decide where solid timber members, glued laminated timbers and laminated wood sheeting could be used most effectively, optimally utilizing the specific characteristics of these materials according to structural, processing and environmental criteria.

4.1 Data Acquisition and Registration Methodologies

The section above discusses the registered bits found in timber and the information the it processes. This section will discuss data acquisitioning technologies used to convert physical data into digital data.

Digitizer Arm

One approach to capturing physical data is by use of a digitizing arm with several degrees of freedom. Each joint is equipped with a sensor measuring the angle. From this data, the spatial point of the arm tip can be calculated (Pottmann, Asperl, Hofer, & Kilian, 2007). The Microscribe 3d desktop digitizer (Figure 27) is a manually operating digitizing tool that allows discrete points on a physical model to be entered directly into a 3d modeling environment. The Microscribe allows point clouds of any size to be constructed by placing the contact tip against the object and clicking. This method is very well suited for capturing the curvature of a model, in this case the curvature of a branch.

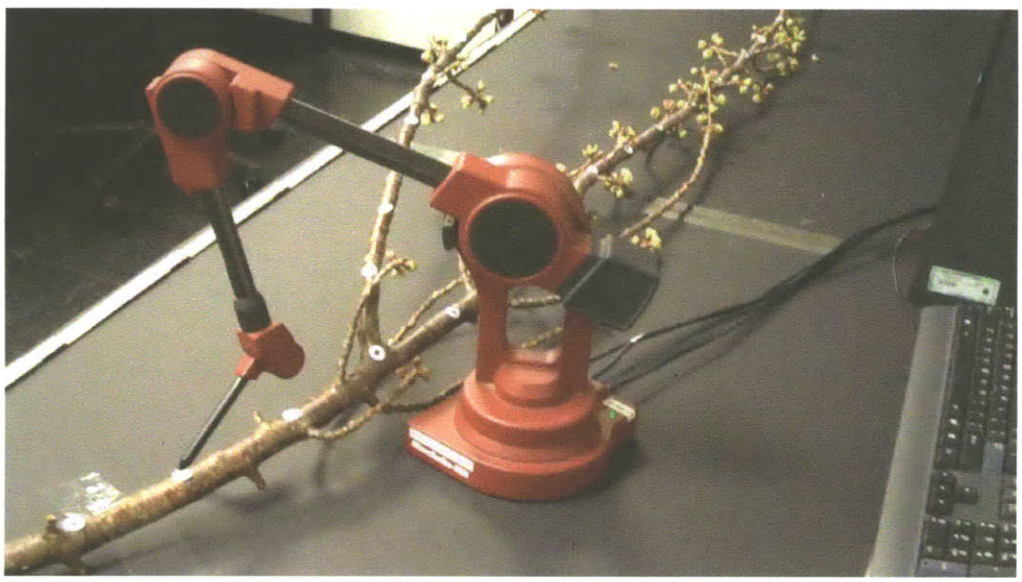


Figure 27 Microscribe 3d Digitizer scanning of a branch

Optical Scanning Devices

3-dimensional scanning devices are largely based on optical technologies. Near-range scanners, which measure objects of a size less than a few meters, are typically used with a combination of laser projection and detection of the projected stripes or patterns with one or more cameras (Pottmann et al., 2007). The Minolta Vivid 700 3d scanner is a laser-scanning device that allows the exterior surface of physical objects to be captures within a digital environment with the ease of a digital camera. Associated software allows the captured image to be saved in a variety of standard formats for export to all common digital design environments. The Minolta 3d scanner discussed here captures data in a similar fashion to the technologies used in the timber construction industry by collecting point clouds of scanned timbers.

4.2 Digital Reconstruction of Natural Structures

Digital Reconstruction starts with data acquisition. Three-dimensional scanning devices are used to produce measurement data from three-dimensional objects. The output is points on a surface(Pottmann et al., 2007). In this thesis a 3d digitizer was used in digitally reconstructing branch elements.

Point Clouds

The measurement data taken from a 3d digitizer or 3d scanner consists of large number of points referred to as point clouds. These data points are precise locations or coordinates of points on a surface. In a 3d scan only the regions of the surface that are directly visible from the vantage point of the scanner will be captured. For the purposes of this thesis the use of a 3d digitizer was used to generate a 3d point cloud of the curvature in each digitized branch.

Digital Reconstruction Through Curves

In this thesis NURBS curves are used in reconstructing the natural curvature of each branch using the point cloud generated by the Microscribe 3d digitizer. Non-uniform rational B-spline (NURBS) curves have weights associated with the control points used to draw the most complex planar and spatial freeform curves (Pottmann et al., 2007).

Bezier, B-spline and NURBS curves are defined using a small number of control points. From the control points, a smooth curve is derived using a geometric algorithm. Interpolation is one approach to interactive curve design with control points. Interpolation requires the designer to define a few points an algorithm finds a curve that passes exactly through these points. Because there are infinitely many different interpolating curves that pass through the same points, you have to provide additional input such as curve tangents in this interpolation (Pottmann et al., 2007).

Digital Reconstruction Through Surfaces

The concepts of curves can be generalized in the study of surfaces. Surface geometry can be studied analytically by mathematically representing a surface parametrically, explicitly and implicitly. In a parametric representation the coordinates of a surface depend on two different parameters u and v. The parameters u and v assume all values in a two-dimensional region. Every pair of parameters u and v that define a point (u,v) of a given region is mapped to a surface (Pottmann et al., 2007). For every surface example listed below traditional, ruled or free-form a set of (u,v) coordinates which describe that given surface can be extracted and used as reference in mapping a given geometry.

Traditional surface classes are largely based on a simple "kinematic" generation. They are swept by a profile curve. For example, an extruded surface can be obtained by translating a curve along a straight line (Pottmann et al., 2007).

Surfaces generated by a moving straight line are called ruled surfaces. Cylinders, cones, one-sheet hyperboloids, and hyperbolic paraboloids are surfaces that carry families of straight lines. By definition, they contain a continuous family of straight lines called generators or rulings and the curve they move along is called a directrix (Pottmann et al., 2007). Double ruled surfaces carry two different families of rulings. An HP surface or hyperbolic surface is an example of a double ruled surface.

Freeform surfaces offer higher flexibility. Bezier surfaces and B-spline surfaces are categorized as freeform surfaces. Bezier surfaces and B-spline surfaces are derived from Bezier and B-spline curves.

5 Approaches to Timber Mapping

There are three approaches to mapping timber onto a surface: Timber > Surf, Surf > Timber Growth and a hybrid of the tweo. The first method Timber > Surf requires a library of timber elements to be mapped onto a surface, re-describing the original surface. The Second method Surf > Timber Growth requires a surface to be predefined and used as a lattice or scaffold for the growth of timber elements. The last method described here is a hybrid of the two where you have a pre-defined surface and you use this as a lattice and in turn use the new grown structure as elements to build upon. This thesis explores the first method Timber > Surf through a library of timber elements mapped onto a surface.

5.1 Digital Framework

The digital framework for this thesis includes data acquisition of three-dimensional curvature of a branch using a Microscribe 3d digitizer. With this 3d digitizer a point cloud is generated directly in Rhino 3d modeling environment. Each set of points is then connected by a 3d spline reconstructing the 3d curvature of a given branch. A set of 3d splines can be cataloged and used in re-describing a given surface by extracting the (u,v) coordinates of that surface and finding the best fit from this catalog to be mapped onto the given surface. The framework can be represented as follows:

Timber > Microscribe 3d digitizer > Rhino > Surf > Map > Prototype

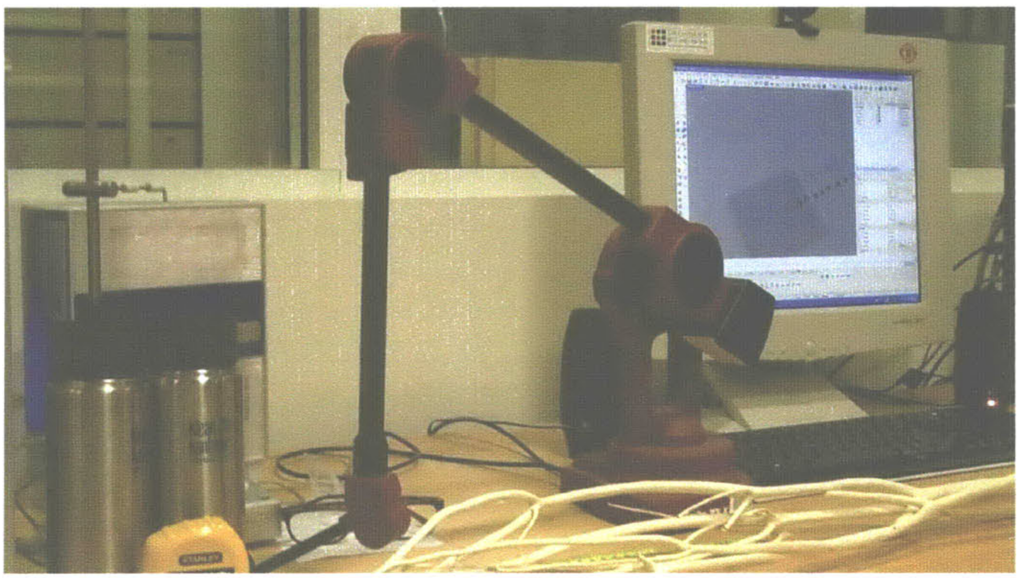


Figure 28 Microscribe 3d Digitizer

The first step in this framework is to digitize the branch using a Microscribe 3d digitizer (Figure 28) and generate a point cloud directly in Rhino 3d modeling environment.

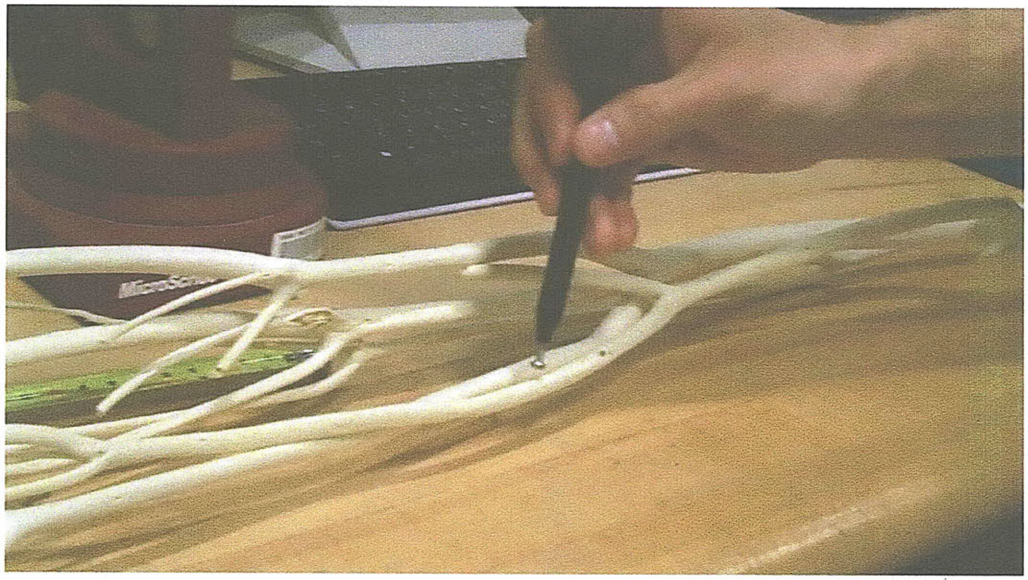


Figure 29 Mitsumata Branch Digitization

The point cloud is generated using the Microscribe 3d digitizing arm and pedal. The end of the arm (Figure 29) is placed over the branch and the pedal is pressed creating a point on screen. The arm is moved from point to point until a point cloud describing the branch has been generated on screen (Figure 30).

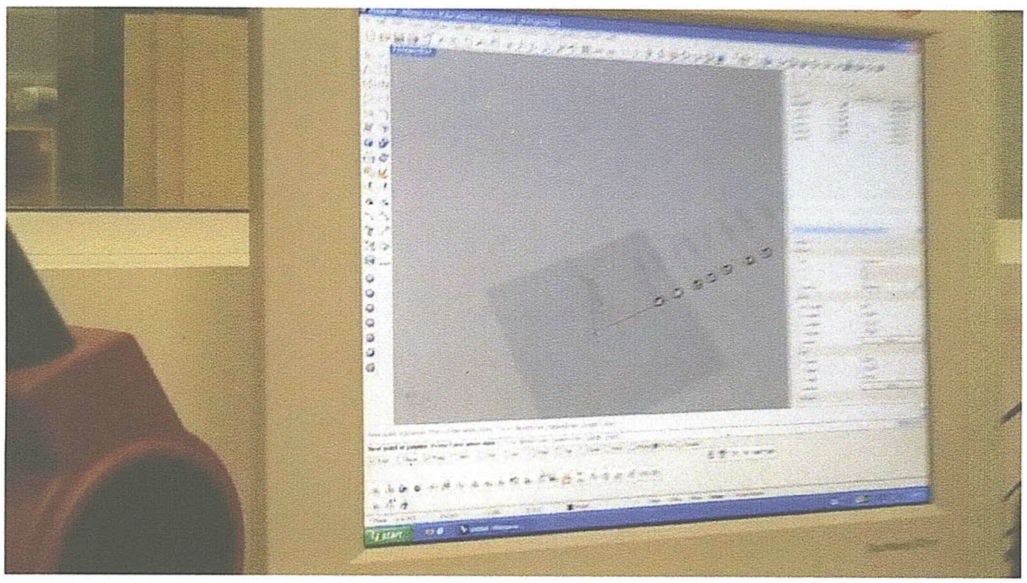


Figure 30 Mitsumata Branch Digitization > Rhino

Cataloging

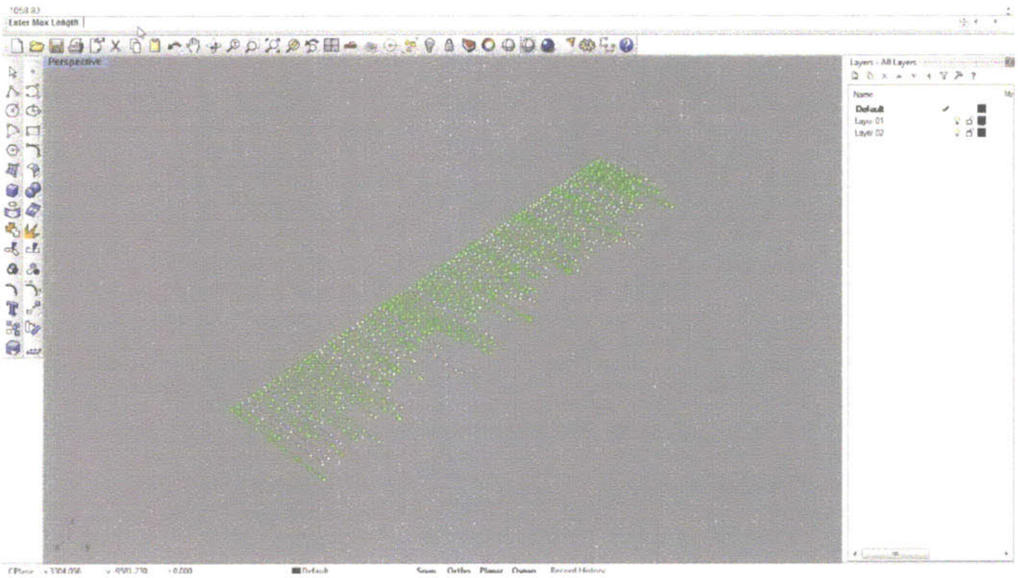


Figure 31 Catalog of Branches Rhino Screen Capture

Once a set a branches as been digitized and the curvature has been reconstructed, each branch can be cataloged (Figure 31) into a set of branches or 3d splines within a 3d modeling environment.

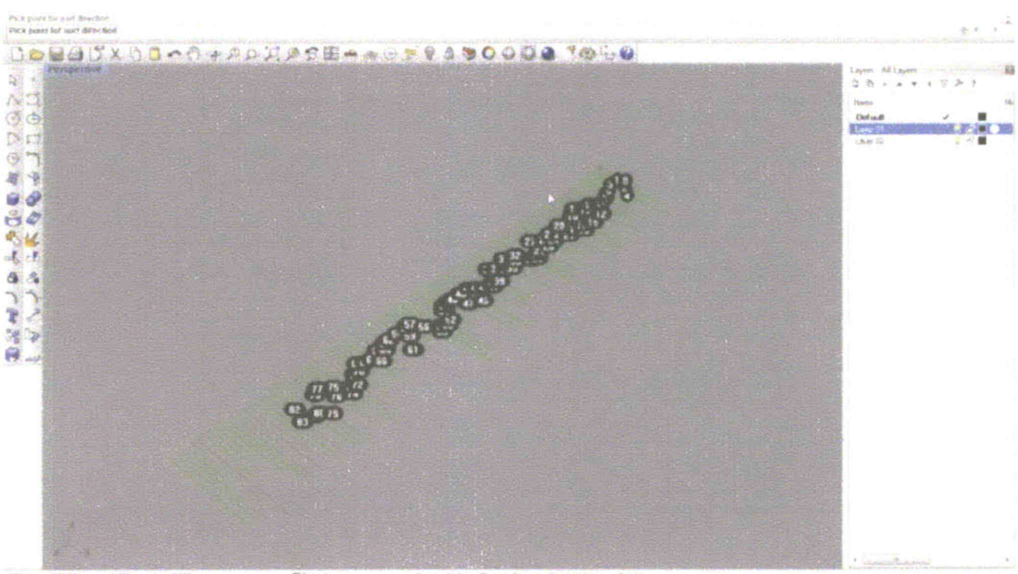


Figure 32 Labeling of Branches Rhino Screen Capture

The set of branches must also be given an identification by adding a text dot

(Figure 32) in Rhino so it may be tracked during the mapping process.

UV Point Definition

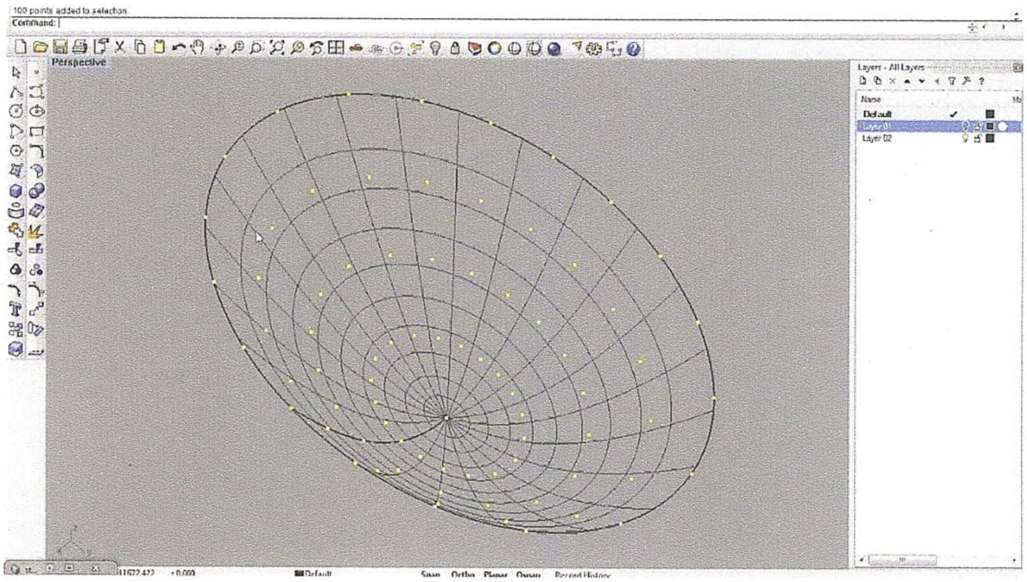


Figure 33 UV Point Extraction Rhino Screen Capture

For any given surface traditional, ruled or free-form a set of (u,v) coordinates which describe that surface can be extracted (Figure 33) and used as reference in mapping a given geometry. In this case a Elliptic paraboloid was used.

Best-Fit

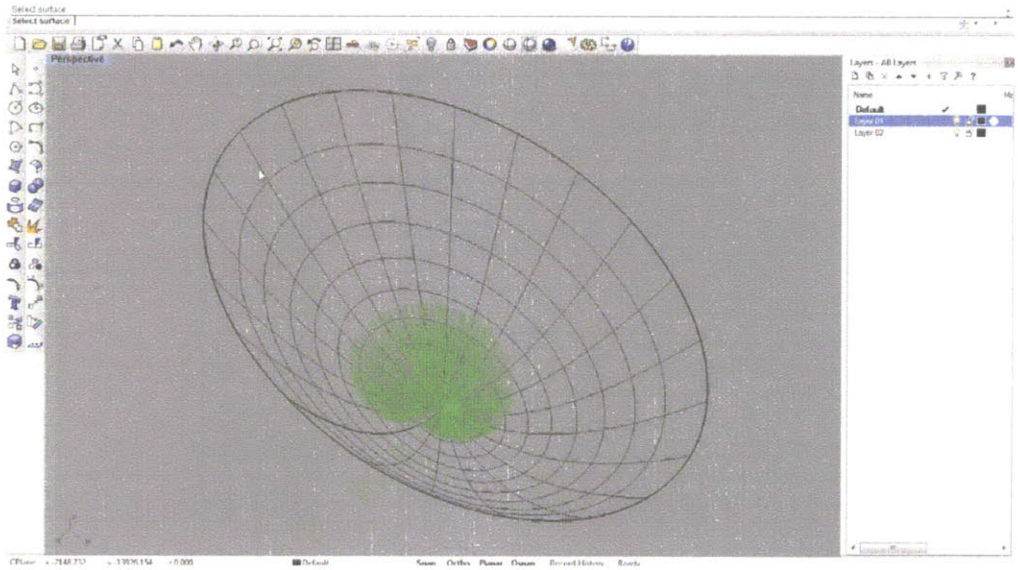


Figure 34 Mapping of Branches using Best-Fit Rhino Screen Capture

Once the (u,v) coordinates have been extracted a "best-fit" algorithm is used which measures the length between points on a given surface and searches through the catalog of 3d spline curves or branches and orients this branch at this location (Figure 34). The algorithm then measures the next distance using the new end point given by the newly placed branch and the next (u,v) coordinate and searches through the catalog of branches finding the best fit and places that branch in that location. The algorithm goes through these steps iteratively until all possible branches are used or there are no branches to choose from.

Auto-Labeling

A second script is used to auto label each mapped branch. The algorithm places a text dot using the branch identifier as text so each newly mapped branch can be identified in space (Figure 35).

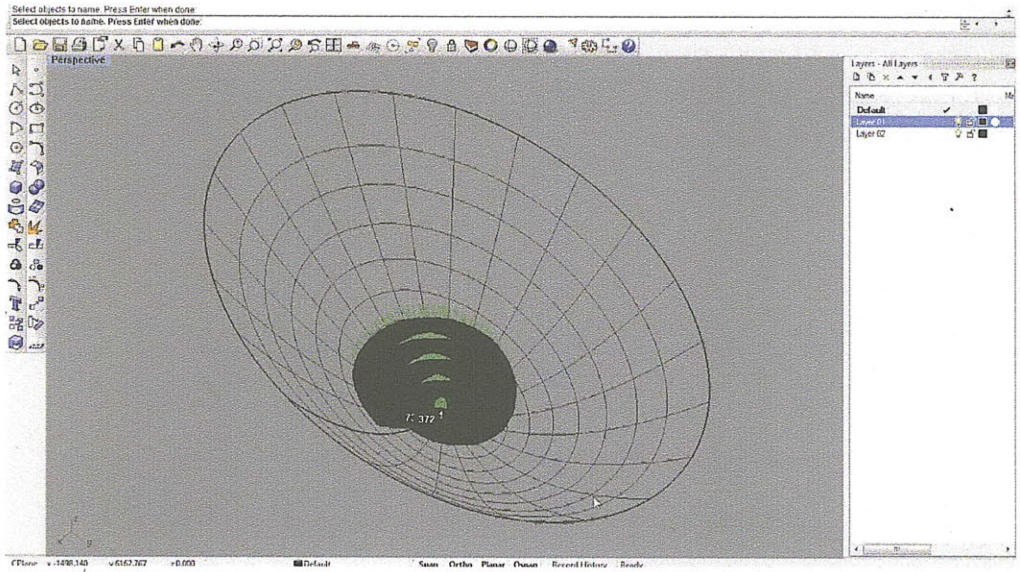


Figure 35 Add Text Dot to Branches Rhino Screen Capture

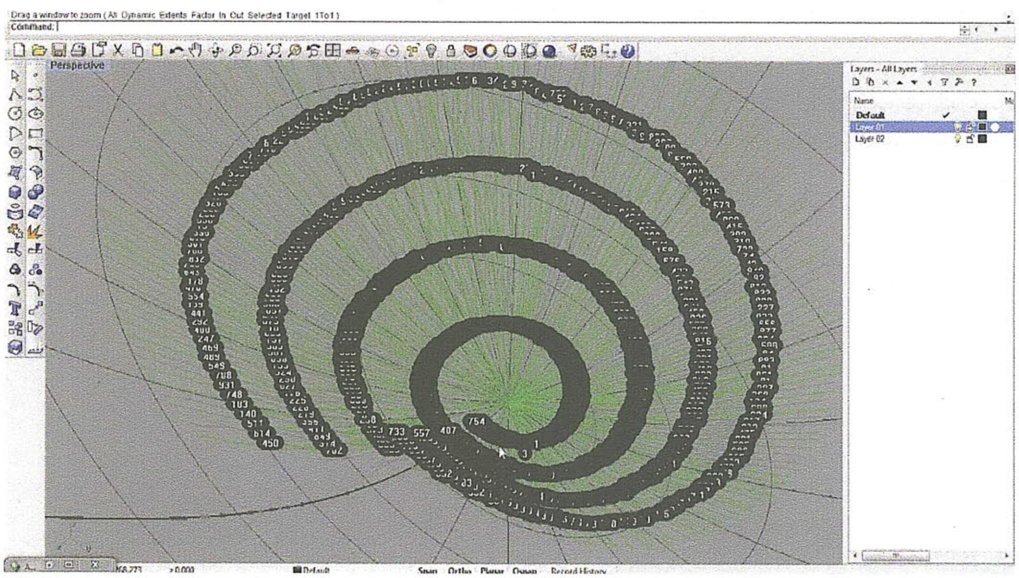


Figure 36 Add Text Dot to Branches Rhino Screen Capture

Pipe Surface Definition

Once all branches have been mapped onto a surface a pipe surface definition is used using an envelope of spheres of equal radius whose centers lie on the spline curve (Figure 37).

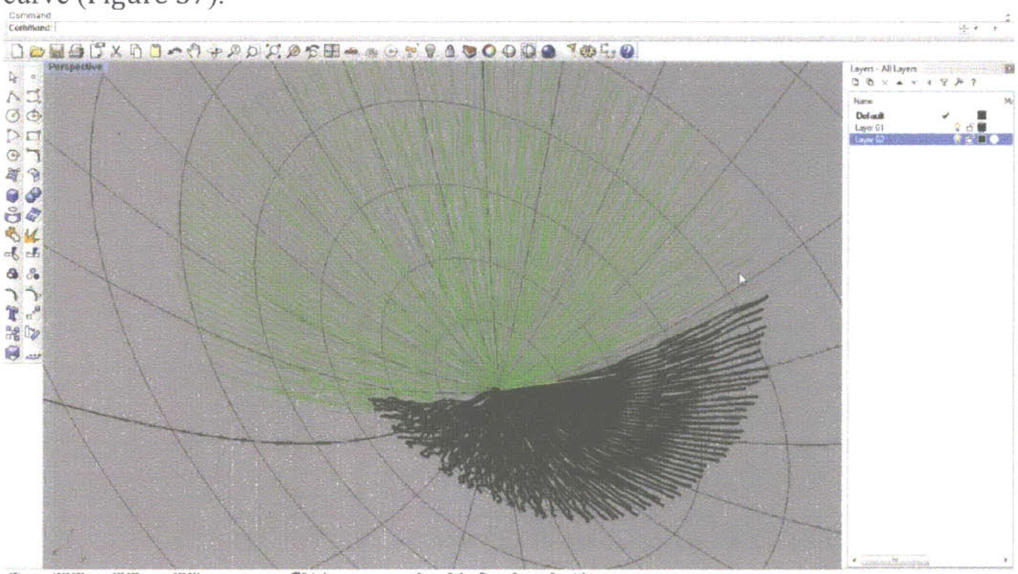


Figure 37 Pipe Surface Definition Rhino Screen Capture

Surface Verification

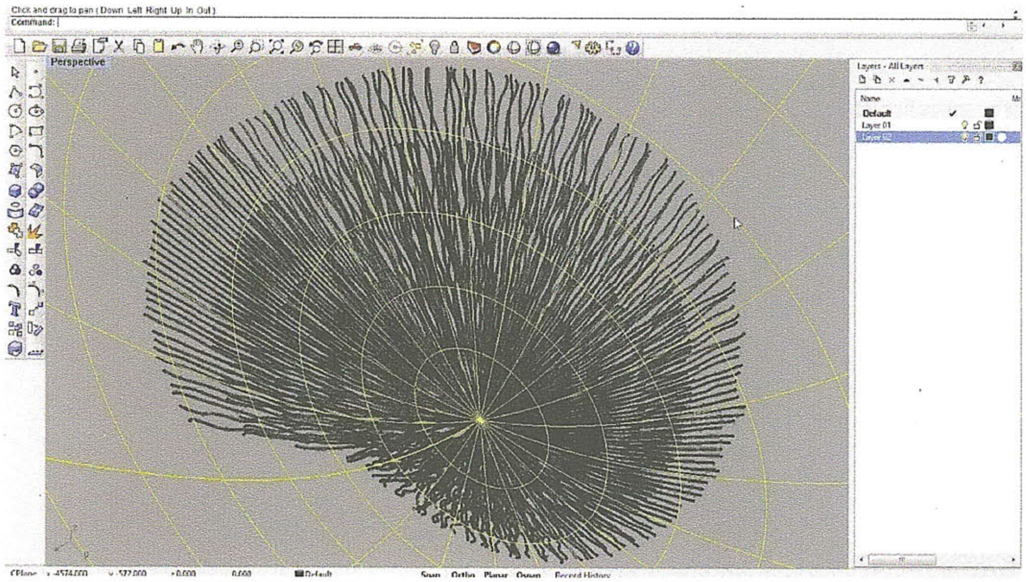


Figure 38 Surface Verification Rhino Screen Capture

The newly generated surface can be verified against the original elliptical paraboloid surface (Figure 38).

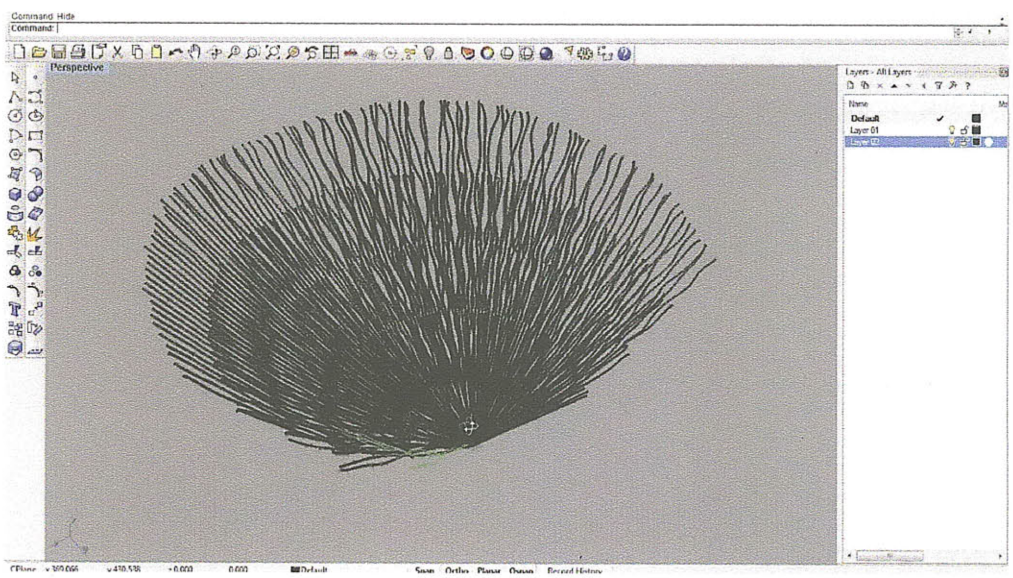


Figure 39 Surface Definition

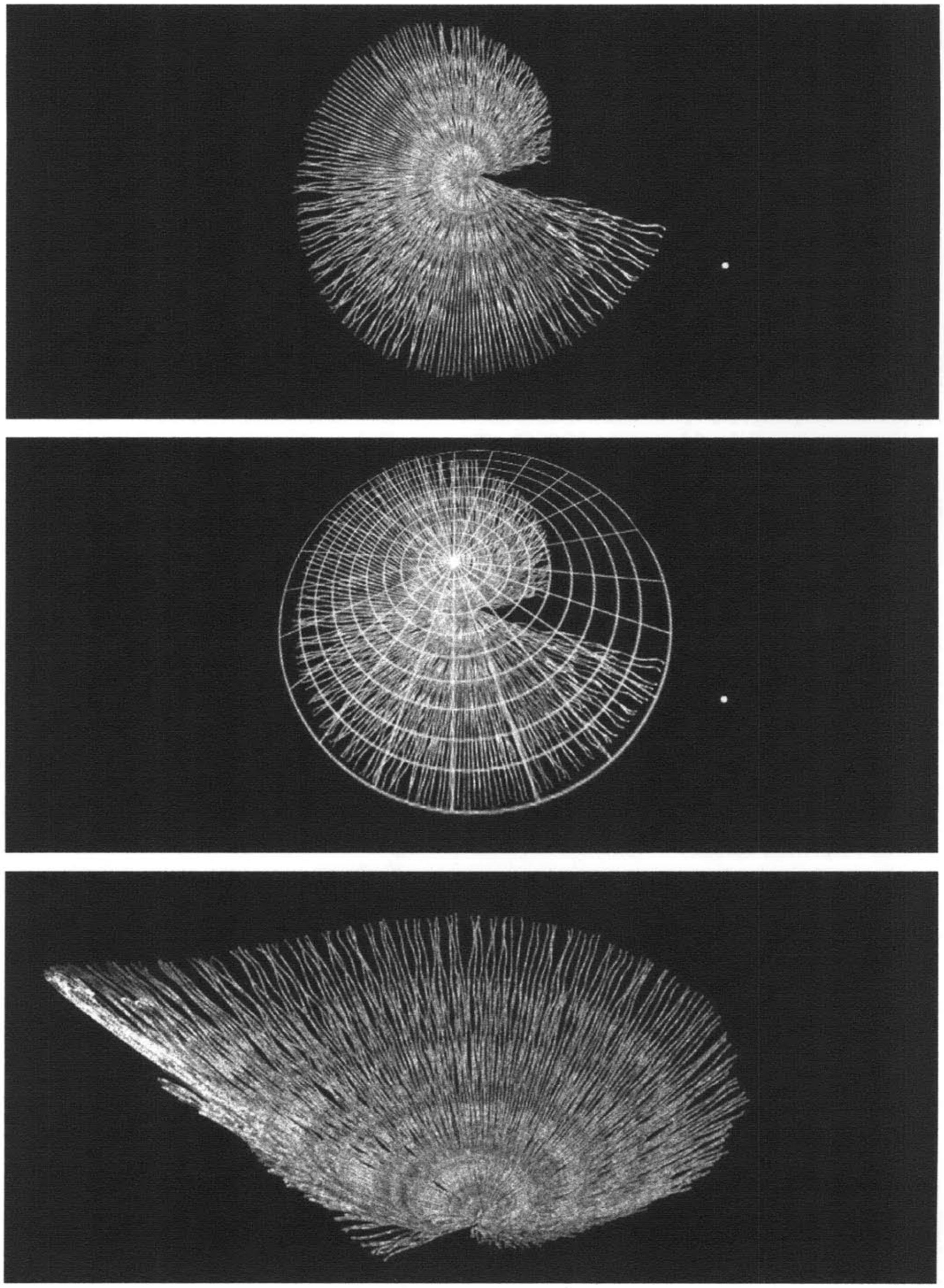


Figure 40 Elliptical Paraboloid Surface Definition

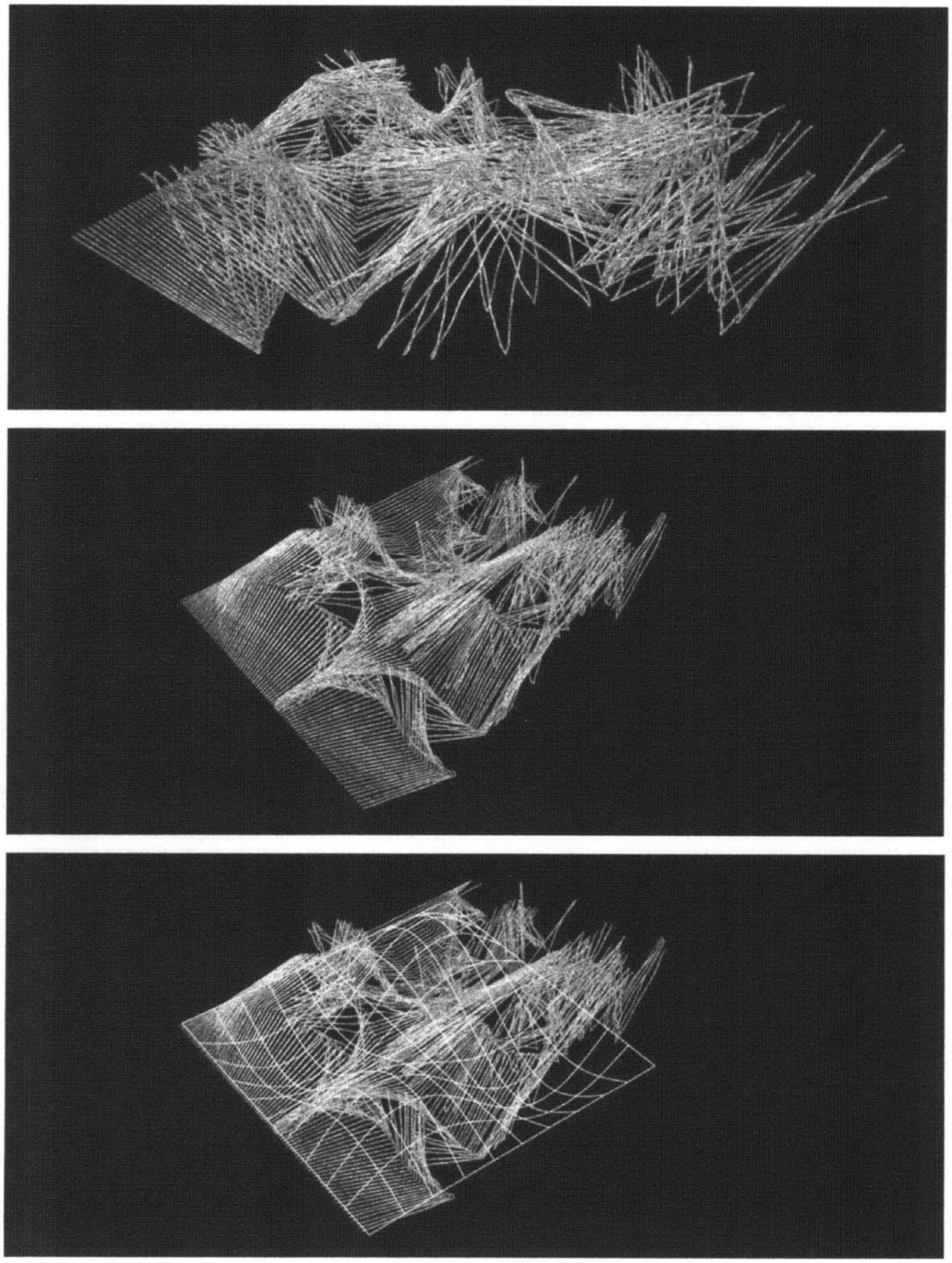


Figure 41 Sine Surface Definition

5.2 Prototype

The prototype made from 18 Mitsumata branches 36"-48" in length had an average ½" diameter. The timber > surf method was used in creating the prototype. The use of 18 Mitsumata branches were digitized using the Microscribe 3d digitizer and mapped onto a section of a surface (Figure 42). The algorithm used for this mapping used the mid-point of each branch to connect one branch to the next creating three branch splines mapped onto a surface.

Figure 42 Prototype Surface Definition

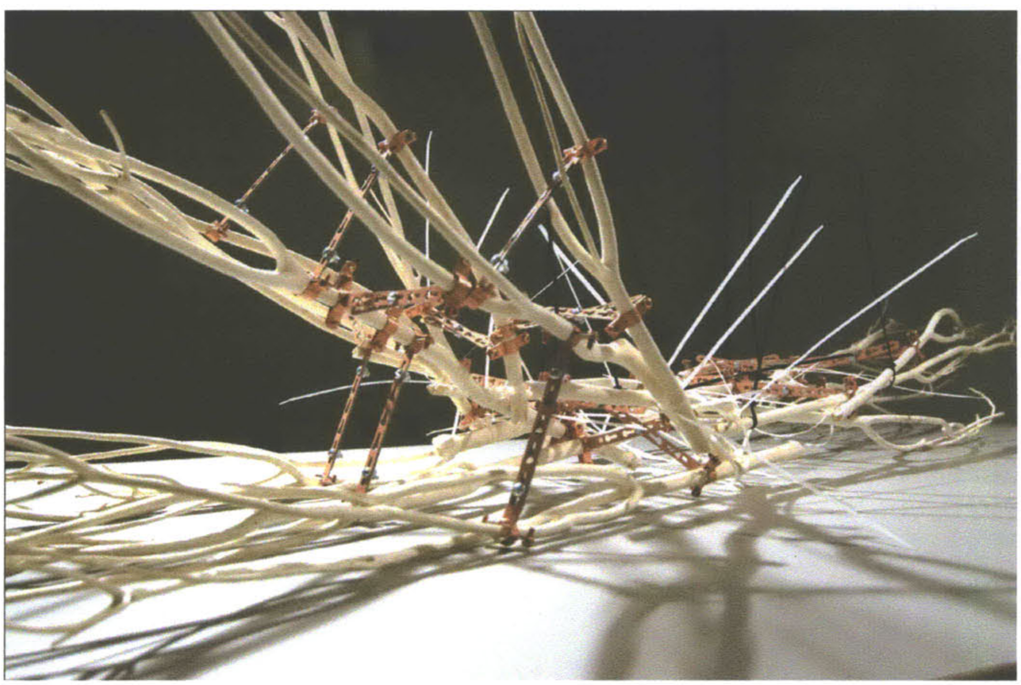


Figure 43 Prototype Photo

The horizontal connection between mapped splines was resolved using an off-the shelf plumbing connection with a collar placed on each branch. The adjustable collar allowed for the correct angle of each branch and added lateral support from spline to spline.

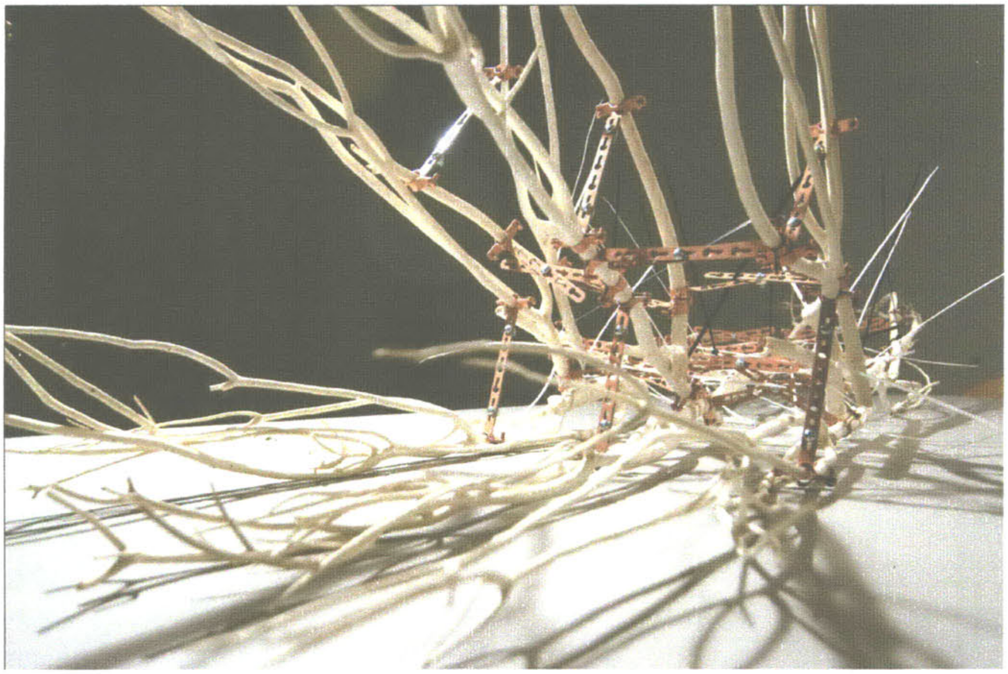


Figure 44 Prototype Photo

The branches were connected using zip ties connecting one branch to the next in the vertical direction (Figure 44) creating each spline along the surface. The use of zip ties allowed the flexibility required to angle each branch in the correct orientation with the added support of the horizontal connections.

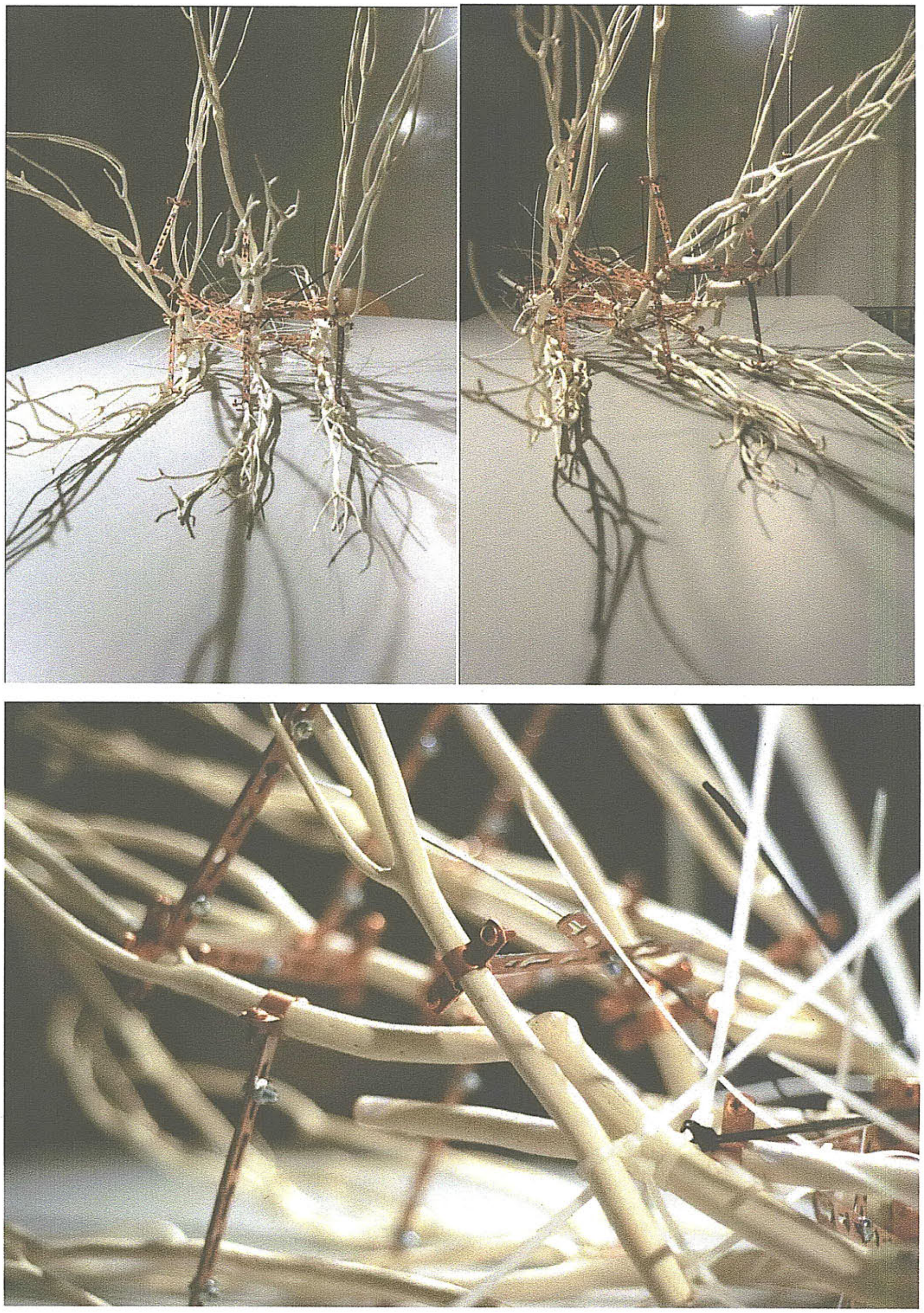


Figure 45 Prototype Photo

6 Conclusions

We are at a point in time when we are able to capture what our materials compute. In the case of timber, the material is processing information at every stage of it use from growth to built form. The material must negotiate natural and unnatural external forces applied on to it. In construction the material must compute the loadbearing forces, which are applied and use different elements generated during growth to do this.

Designing with this information can serve as a driver for form generation using the natural strain and stresses found in the material itself and by using the natural curvature found in timber. The bits of information registered within timber, such as curvature as demonstrated in this thesis can be mapped onto any given surface and used to generate new forms.

Through an exploration of wood as a natural material in design and construction of complex geometrical timber structures, the notion of using timber as a raw material has emerged and used in generating new forms of design. The results of this investigation lead to a digital framework for capturing physical data into a digital environment and ability to use this data for design in the spirit of natural architecture through digital means.

This workflow allows the capturing of natural curvature found in timber through the use of a Microscribe 3d digitizer and generating a point cloud that can be used in reconstructing a 3d spline representation of a timbers natural curvature. The splines are then mapped onto any given surface. A prototype has been built to demonstrate the success of this digital framework in translating physical data into digital data and back into physical representation. The manipulation of natural materials can be explored through digital means by encoding the natural properties of any given material. This thesis focuses on the single property of natural curvature. Future iterations may use timbers ability to branch, graft or build knots.

This model of acquiring physical data and building digital representations and then building physical models allows designers to leverage the use of computation by building customized tools that encode the natural properties found in nature and materials. Through computation we can represent explicitly the limits of our materials and represent systems found in nature. These results were very close to my initial thoughts on our ability to build computational representations of natural systems and use them for design.

The bigger question for me was in this universe made of bits where every molecule, atom and elementary particle are continuously processing information how may we design using this information and how may we begin to think of manipulating our natural environment around us. For me, this thesis has shown that we are able to capture this data and use it for design. This thesis has also suggested that we can begin to think of methods in which we can manipulate the growth of our natural environment and aid in the design of nature itself. During this thesis a friend introduced me to a website called Next Nature. This website is about human attempts to cultivate nature, humankinds rising of next nature, in an age where the made and the born are fused. Our relationship with nature is changing.

6.1 Contributions

The contributions for this thesis include the established digital framework for digitizing the curvature of a timber and translation of physical data to digital data and outline of approaches to timber mapping. This thesis also contributes the idea that we can capture physical data and build digital representations that can be used in aiding the growth of natural structures. Additionally, this thesis contributes the construction of a physical prototype as proof of concept that we can capture physical data, build digital representations and build physical models of our manipulations using natural systems.

Digital Framework

The digital framework shown below should be used to translate 3d curvature of timber from physical data to digital data through a 3d digitizing process and conversion of point cloud data to 3d spline.

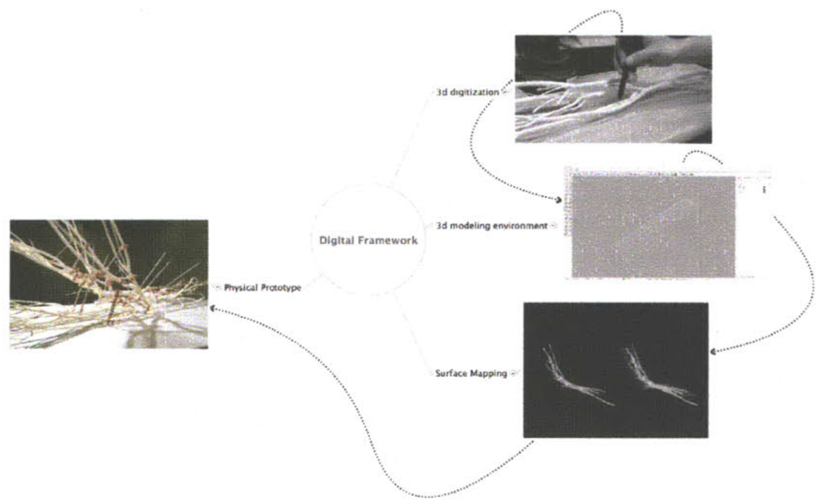


Figure 46 Digital Framework Diagram

Approaches to Mapping

This thesis outlines three methods for timber mapping approaches. The first method Timber > Surf requires a library of timber elements to be mapped onto a surface, re-describing the surface. The Second method Surf > Timber Growth requires a surface to be pre-defined and used as a lattice or scaffold for the growth of timber elements. The last method described here is a hybrid of the two where you have a pre-defined surface and you use this as a lattice and in turn use the new grown structure as elements to build upon. This thesis explores in detail the first method Timber > Surf through a library of timber elements mapped onto a surface using 18 branches and a "best-fit" algorithm described in detail in the sections above.

6.2 Next Steps / Future Work

This thesis scratches the surface on what materials compute and how we design with this information. This thesis describes in detail the bits of information registered within timber during growth and interactions and processes of information, which occur within wood. The use of a digital framework was utilized in imagining new buildings in the spirit of natural architecture. This thesis also explored the use of wood as a natural material in the design and construction of complex geometrical timber structures and proposes that future timber structures can be grown and in combination can be used with typical timber construction methods.

There are many areas in which future works can provide further investigation. The use of natural curvature found in timber, as design input was the only property explored. Branching or knots can also be used in the future design of timber structures. Growth machines could be engineered to produce the desired curvature of timber during its growth process as the shipbuilders of the 14th century did. Similarly, we could devise machines that aid in the growth of these timbers and generate forests of curved timbers, which span longer distances than currently possible by laminated timber construction or timber meshes generated from grafting methods. The ability to grow forests of curved timbers that span longer distances than currently possible by laminated timber construction, could lead to timber structures that require very little support. These long spanning timber structures using less timber members would allow newly complex geometries to be explored. Also, having ready-made building components would reduce the prefabrication currently required by complex geometrical timber structures. In addition, having timber structures built using grafting methods would lead to incredibly strong joint systems that have been perfected by nature similar to the welds described by Mattheck where one member is grafted onto another as shown in (Figure 47).

Mattheck also describes a trees ability to heal itself. When a leading branch dies by way of infection or lack of water, sunlight, etc. a secondary branch will grow from the base of the tree and heal the leading branch and together grow into a new form as shown in (Figure 48). If we had living components to buildings we could utilize their ability to heal themselves and grow areas of building that were far stronger than those engineered by men or have buildings that repair themselves when damaged. Our relationship with nature is changing.

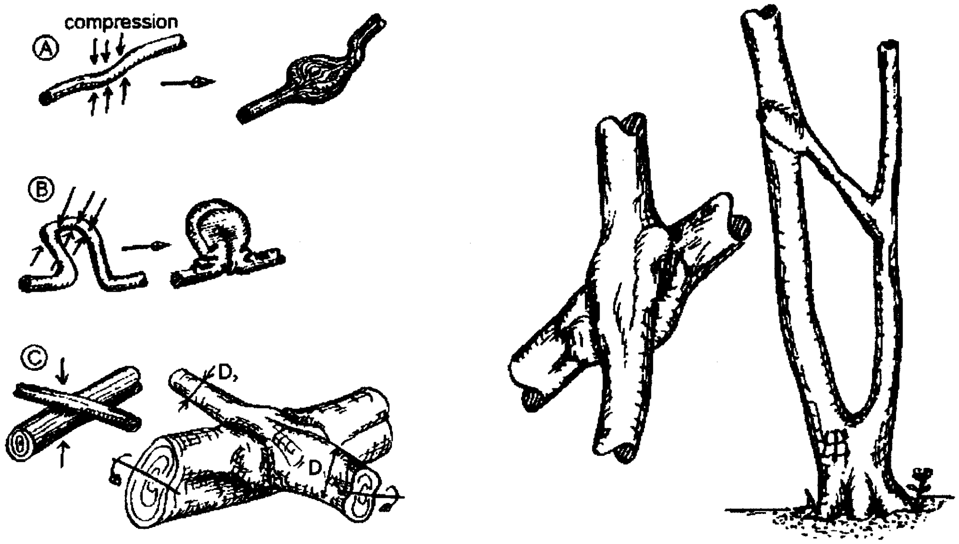


Figure 47 Typical Tree Welds A: knot formation b: post-horns C: 'welds' grafts (Design in Nature)

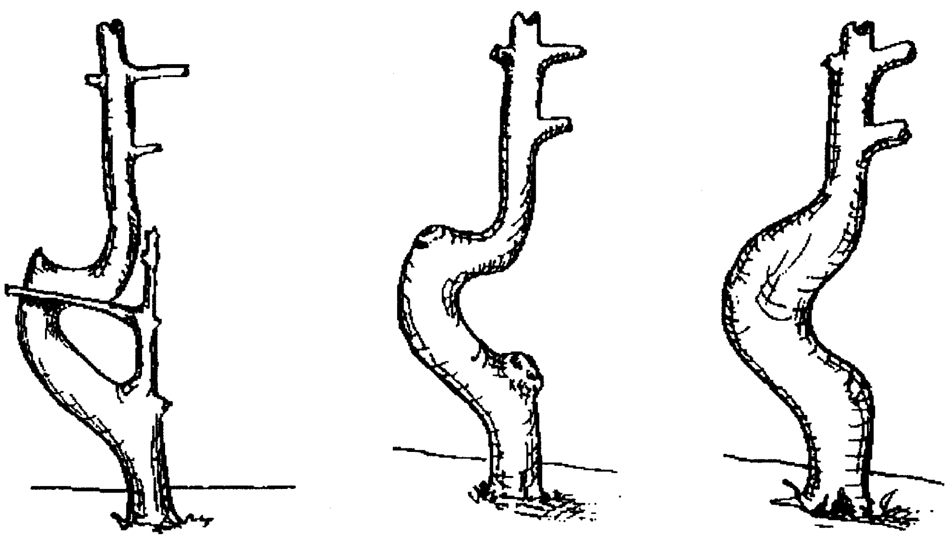


Figure 48 Tree Ability to Heal (Design in Nature)

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List of Figures

List of Tables